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Decreasing lead time of vacuum process of x-ray tube head production by 50%

Diplomityö, joka on jätetty opinnäytteenä tarkastettavaksi diplomi-insinöörin tutkintoa varten

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Työn valvoja: Professori Jouni Partanen
Työn ohjaaja: DBS Leader Niku Jalkanen

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Diplomityön tiivistelmä

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Tiivistelmä

Tämän diplomityön tavoitteena on selvittää voiko putkipäiden tyhjiöprosessia lyhentää vähintään 50 % ilman negatiivista vaikutusta tuotteiden laatuun. Nykyään tyhjiöprosessi on putkipäätuotannon pullonkaula. Prosessi estää valmistettavien tuotteiden jatkuvan virtauksen ja pakottaa valmistamaan laitteita erissä.

Tyhjiöprosessin merkittävää lyhentämistä pidetään mahdollisena. Tätä ei ole tehty, sillä prosessin lyhentämisen vaikutuksista ei ole tehty tutkimuksia. Ei ole myöskään tiedossa, kuinka suuri määrä ilmaa tai kosteutta putkipään sisällä aiheuttaisi ongelmia. Eri tuotteiden rakenteelliset ja toiminnalliset erot tekevät tarvittavan tyhjiöajan arvioimisen vaikeaksi. Lisäksi kullekin putkipäälle suoritettavat lopputestit eivät täysin varmista tyhjiöprosessin riittävyyttä. Tästä syystä on todistettava, että prosessi tuottaa tasaista laatua.

Tässä työssä tehdään testisuunnitelma, jolla voidaan tilastollisesti todentaa lyhennetyn prosessin toimivuus. Testien on tuotettava korkea varmuus lyhyen prosessin toimivuudesta, jotta lyhyemmän prosessin käyttöönottoon ei liity merkittävää riskiä laadun heikkenemisestä. Tuoteryhmien suuren lukumäärän vuoksi vain osa testataan. Samaa testausprosessia voidaan tarvittaessa soveltaa myös testien ulkopuolelle jääviin tuotteisiin.

Työn toinen osa liittyy muihin tapoihin, joilla tyhjiöprosessia voitaisiin parantaa, tyhjiöajan lyhentämisen lisäksi. Tässä osassa arvioidaan nykyistä pohjapiirrosta, materiaalivirtoja ja tuotannon visuaalista ohjausta.

Testien pitkän keston vuoksi kaikkia testejä ei voida saattaa loppuun ennen tämän työn valmistumista. Tästä syystä esitetään testausprosessi ja ehdotuksia prosessin parantamiseen. Testien todennäköinen lopputulos esitetään ja tulevaa tuotannon ohjausta suunnitellaan sen mukaan.

Avainsanat Tilastollinen testaus, Lean, 5S, tuotannonsuunnittelu, kokoonpano, tyhjiöteknologia

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Abstract of master's thesis

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Abstract

The target of this thesis is to investigate if it is possible to decrease the lead time of tube head vacuum process by at least 50 % or more. Currently the vacuum process is a bottle neck in the tube head production. It inhibits the continuous flow of products and forces the production to be run in batches.

It has been hypothesized that the process could be significantly shortened. This has not been done since there has been no research to support this hypothesis. There also isn't enough understanding on how much air or moisture would cause problems in a tube head. Structural and operational differences of the products make it difficult to estimate how much vacuuming is required for a specific product. Furthermore, the final testing of each finished products can't fully verify, if the vacuum process has been sufficient. Consequently, the process needs exhibit the ability to produce steady quality.

This thesis will present a test plan that is used to verify statistically, if the vacuum process could be made shorter for all tube heads. This is to be accomplished with a high confidence and reliability so that there is very little risk of any quality issues if a shorter process is to be implemented. Due to high amounts of different products, only some will be tested. However, the same testing process can later be used for all products which will be left out of the initial testing.

Another part of this thesis presents how the current state of the vacuum process could be improved in addition to shortening the vacuuming time. This part will include evaluating the current layout, material flows and visual controls of the process.

Because of the long duration of each test, all testing will not be completed by the time this thesis is finished. What will be presented, however, are the testing process and suggestions for future development. The likely outcome of the testing will be presented and the future production plans will be designed accordingly.

Keywords Statistical testing, Lean, 5S, production planning, assembly, vacuum technology

PREFACE

This thesis was done for Kavo Kerr Group as a part of lean conversion process. The significance of this project became apparent to me while working as a manufacturing engineer in the tube head producing minifactory. The vacuuming process is by far the longest single process in the entire tube head production process.

The desired future state of the vacuuming process was clear from the beginning, but the challenge of getting there proved to be great. Changing a process that produces practically perfect quality products was met with some doubt. In the end, all those involved with the process saw the benefits of investigating if the vacuuming process was an example of over-processing. Researching this wasn't as easy as originally suspected - a lot of effort was sunk into designing and building the testing environment and running the tests. A special thanks to the people at the electrical department who played a vital role in building and running these tests.

I wish to thank the thesis supervisor, professor Jouni Partanen, for his advice during the process. Many thanks for the help in designing the tests and facilitating the process goes to DBS Leader Niku Jalkanen, who was the official advisor in creating this thesis. Thank you to all the other people involved in the process as well.

I wish to express my gratitude to the people close to me and especially to my better half Dawei Chen. I could not have hoped for any better support.

Espoo 20.5.2016

Jukka Kallio

TABLE OF CONTENT

SYMBOLS USED

%	Percentage
°C	Degree Centigrade
A	Ampere
α	Alpha Level
β	Constant
cm^3	Cubic Centimeter
C	Confidence Level
E_k	Kinetic Energy
f	Number of Failures Allowed
H_0	Null Hypothesis
H_a	Alternative Hypothesis
kV	Kilo Voltage
K	Degree Kelvin
L_D	Desired Lifetime
L_T	Tested Lifetime
m	Meter or Mass
R	Reliability
T	Temperature
Torr	Pressure Unit
V	Volume or Volt
Å	Ångström

ABBREVIATIONS USED

CDG	Capacitance Diaphragm Gauge
CTQ	Critical To Quality
DBR	Drum Buffer Rope
DBS	Danaher Business System
DOE	Design of Experiments
FIFO	First In First Out
FPY	First Pass Yield
HV	High Voltage
JIT	Just-In-Time
MRP	Material Requirements Planning
PD	Policy Deployment
PDCA	Plan Do Check Act
PVD	Physical Vapor Deposition
SRG	Spinning Rotor Gauge
STP	Standard Temperature and Pressure
STUK	Säteilyturvakeskus
SW	Standard Work
THA	Tube Head Assembly
TOC	Theory of Constraints
TPM	Total Productive Maintenance
TPS	Toyota Production System
UHV	Ultrahigh Vacuum
VOC	Voice of the Customer
VUHV	Very Ultrahigh Vacuum
VSM	Value Stream Mapping
WIP	Work in Process

1 INTRODUCTION

This thesis is produced for Kavo Kerr Group, which provides technology for dental businesses. Kavo Kerr Group is part of Danaher Corporation. The Tuusula site, where this research is conducted, manufactures imaging equipment. These machines are used by the worldwide dental market.

1.1 Research background

High voltage (HV) minifactory produces tube heads for all the X-ray machines manufactured in the Tuusula factory. The total demand and the variation between different products are defined by the production plans of the final assembly lines, which in turn, are created according to customer orders. The assembly lines, or minifactories, assemble and test the X-ray machines. No X-ray machine can be completed without the tube heads made at HV production. HV production is therefore vitally important for fulfilling the orders.

The purpose of the vacuum process is to make sure there is no significant amount of air or moisture left inside the tube head once they have been filled with oil, then sealed and prepared for customer use. Any impurities within the oil can cause arching inside the tube head assembly (THA) when the product is being used.

The vacuum process, in its current state, is very time consuming. There is a strong consensus that the process lead time could be made significantly shorter by improving the process and by acquiring enough statistical data to determine the optimal time required for vacuuming.

When the process was originally created, the vacuum time was set to a certain level that was proven to produce quality products. At the time, it was not viewed necessary to make the vacuuming process shorter. Research was therefore not conducted to find out how long of a vacuuming still has a positive impact on the quality of the products. Consequently, the cycle time has remained long and now creates a bottleneck to the tube head production process.

There are several reasons why the vacuuming process time should be reduced if possible. Possible increase in future demand, large amount of different products and limited resources together create this need to significantly shorten the vacuum process.

Danaher has strongly adopted the lean philosophy that aims to minimize waste in processes. Decreasing lead time of a production process reduces the amount of work in process (WIP) and the value of inventory required for keeping the process running. Lead time reduction would also decrease the required amount of buffer stock of fully assembled tube heads, since reacting to changes in customer demand would be faster.

1.2 Research scope

This thesis concentrates on the vacuum process of x-ray tube head production at HV minifactory. Main focus of the research is to find out if it is possible halve the vacuuming time of all tube heads, without causing a negative impact on quality. This will include creating of a test plan and the equipment required to carry out the testing.

The scope of possible time saving research will more specifically be limited to two process steps: vacuuming before oil is poured into the tube heads and the vacuuming that follows the oil pouring. Optimizing the time spent on other steps, both before and after vacuuming, is not within the scope.

Research will include the highest volume products manufactured at Tuusula factory. The same testing process can later be applied for other products.

Work methods and material flows will also be analyzed for improvement possibilities during the entire vacuuming process. Recommendations for improvement of these processes are to be made by analyzing their costs and benefits.

1.3 Targets of research

The primary target of research is to halve the cycle time of vacuum process in tube head production, without a negative impact on the quality of finished products. This is to be accomplished by gathering enough statistical data of shortened process to prove, with high enough confidence level, that no reduction in quality would occur by reducing the time products spend in the vacuum.

The goal is to create a plan that can be used to investigate the possibility for vacuuming time reduction for all products manufactured in Tuusula factory. During the thesis, tests are to be started or carried out for the highest volume products.

Secondary targets are the reduction of batch sizes and improvement of production control, and thereby go towards one piece flow. These targets can only be achieved if the product's testing has been completed.

1.4 Research methods

The research will be conducted by examining literary sources to find proven solutions to similar challenges in the past. Statistical testing and analysis will be used to define proper sizes of testing batches. Main part of the research is empiric testing to find out how the tube heads react to the shortened vacuuming.

1.5 Research structure

First part of the research consists of related theory acquired from literary sources. Second part is description of the current state of the vacuuming process. These are followed by the future state description and description of the tests that are conducted to test the desired future process. Final chapters will include recommendations for development and the summary of this thesis. Some of these chapters will not in fact be included in this thesis due to their confidential content.

2 STATISTICAL TESTING

This chapter discusses statistical testing as a way of gaining knowledge about a system. The chapter defines the normal testing procedures and illustrates different approaches to testing. The methods will concentrate on practical processes that can be used to gain data and test the performance of manufacturing processes. These methods will later be used to test the assumption that the vacuuming process could be made shorter.

In statistical testing, assumptions presented about the fundamental set need to be phrased as hypotheses. When statistical analysis is performed, we are always testing some hypothesis. Statistical test is a ruling that states, in light of findings made, if a hypothesis must be discarded or not. Test is carried out to find out if a hypothesis is fitting to describe the observations. (Milton 2003, Ropella 2007)

2.1 Hypothesis testing process

A hypothesis is a speculative statement that describes a relationship between variables. Hypothesis testing is the most used tool in scientific research. The testing of a hypothesis is carried out as a sequence of steps. During these steps, data is gathered and analysis done to prove or disprove the hypotheses presented. (Martin 2012)

The hypothesis testing process goes as follows (Martin 2012):

1. Establish the alternative hypothesis (H_a)
2. Establish the null hypothesis (H_0)
3. Decide on the risk one is willing to take for being wrong
4. Decide on the appropriate statistic to test the H_0
5. Draw sample size (n), assess if the assumptions are met for the chosen statistic
6. Decide if H_0 or H_a is true

The first step of hypothesis testing process is to present the alternative (research) hypothesis. The amount of variables in a hypothesis can vary greatly. When a research is started, one or more initial hypothesis are presented. They represent the expected result of the study. (Martin 2012)

There are often multiple variables to be taken into account in the hypothesis. These variables can be divided in two groups: “predictor variables” that are independent variables and “criterion variables” that are dependent variables. (Martin 2012)

Hypothesis can be presented as a directional hypothesis or a non-directional hypothesis. Non-directional hypothesis means that the researcher does not have a clear expectation regarding the direction of the results, while a directional hypothesis is used when the direction is considered clear. Non-directional hypothesis is usually used if there is no previous research or other source of information to suggest the likely outcome of the research. An example of usage of non-directional hypothesis is psychological studies, where the human reaction can’t be estimated without previous knowledge. (Martin 2012)

Second step in the testing process is establishing a null hypothesis. Null hypothesis is the one that will be tested statistically. Nullification of the null hypothesis could be viewed in support of some alternative hypothesis. It could also mean that the hypothesized relation between some parameters does in fact not exist. (Martin 2012)

Third step includes a risk evaluation. There is always a chance that a true hypothesis is rejected or an untrue one is accepted. To decide how great this risk is, the researcher sets an alpha (α) level. The most common level used is $\alpha = 0{,}05$. At this level, the result is considered statistically relevant. In practice $\alpha = 0{,}05$ means that there is a 5 % chance of rejecting a true H_0. When the alpha is reduced, the reliability increases. However, reaching higher reliability also requires larger sample sizes. (Martin 2012)

Fourth step in the process is to decide on the statistic and sampling distribution to be used in testing of the null hypothesis. Sampling distribution gives the testing a statistical foundation. The distribution type is chosen based on the type of variables being examined, the amount of dependent and independent variables, the measuring scales of dependent variables, relationships between groups being compared and the assumptions that relate to the underlying statistic. (Martin 2012)

Fifth step is to take a specified sample size. The data is then screened to make sure it is accurate and doesn't have missing values. During the fifth step it is also assessed if the assumptions of the chosen statistic are met. Sometimes the screening may result in a need to modify the data. (Martin 2012)

In the data screening process, the data is either entered by hand into a computer system or imported straight from a source. It is important to note that all methods of data compilation have some degree of imprecision. Therefore, various methods should be used to check accuracy of the data before performing statistical analyses. (Martin 2012)

During the screening, the missing data is also of concern. Data can sometimes end up missing due to a handling error. Another reason could be that one of the samples in the group has for some reason not given out any data. (Martin 2012)

Sixth step is to decide if the null hypothesis should be accepted or rejected. This decision is based on statistical analysis of the reliable test data that remains after the screening. The decision of rejecting or not rejecting the H_0 is based on α. If the significance probability is less than α, the H_0 is rejected. (Martin 2012)

Rejecting or accepting the null hypothesis is then not a certainty. When the testing is finished, some probability has been reached to support the hypothesis. There is always some chance that the conclusion is not the correct one. (Martin 2012)

2.2 Design of Experiments - DOE

Experiments are performed in many manufacturing organizations to better understand manufacturing processes. Experiments are often conducted in a series of tests which produce quantifiable results. In order to continuously improve product/process quality, it is fundamental to understand the process behavior, the amount of variability and its impact on processes. In an engineering environment, experiments are often conducted to explore, estimate or confirm. In manufacturing processes, the primary interest is often to

explore the relationships between the key input factors and the output performance or quality characteristics. (Davim 2012, Jiju 2003)

DOE has several applications in developing manufacturing processes. These applications include (Jiju 2003):

- Improved process yield and stability
- Improved profits and return on investment
- Improved process capability
- Reduced process variability and hence better product performance consistency
- Reduced manufacturing costs
- Reduced process design and development time
- Heightened morale of engineer with success in chronic-problem solving
- Increased understanding of the relationship between key process inputs and outputs
- Increased business profitability by reducing scrap rate, defect rate, rework, retest, etc.

DOE begins with a hypothesis. Hypothesis can for example suggest that a process could produce equal quality with less processing. Over processing is recognized as one of the wastes to be removed according to LEAN production philosophy. After a hypothesis has been presented, a series of tests will be conducted. That is, if the estimated long term benefits presented in the hypothesis outweigh the costs of testing. (Jiju 2003, Kouri 2009)

Industrial testing process involves following sequence of activities (Jiju 2003):

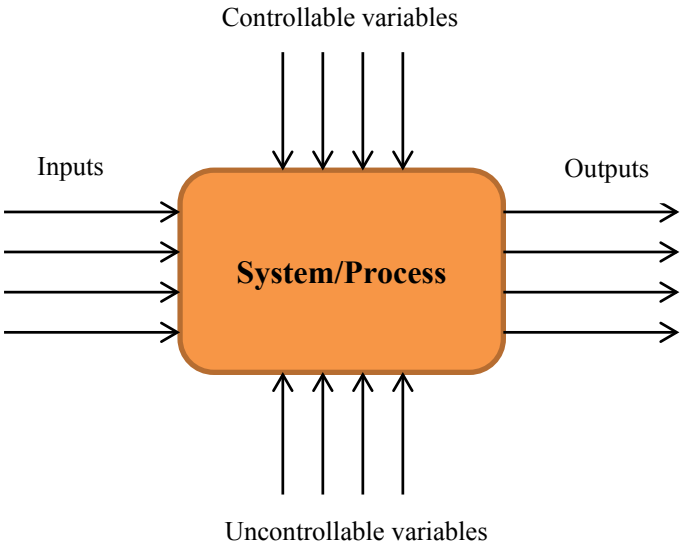
1. **Hypothesis** is presented.
2. **Experiment** is run to test the hypothesis.
3. **Analysis** of the data is done.
4. **Interpretation** of the data.
5. **Conclusion** about the original hypothesis.

Presenting a hypothesis means making an assumption that requires testing. This assumption is the motivation for testing. Experiments are then run to test if the hypothesis is correct. Then the data gained is analyzed so that it can be understood. Analysis also includes putting the data into a statistical form. Next step is to interpret the analyzed data to truly understand the findings. Finally a conclusion is made to decide if the original hypothesis was in fact true. Often the conclusion is that the hypothesis requires more testing, or a completely new hypothesis is made based on the knowledge gained. (Jiju 2003)

DOE can be used to experiment on any industrial process. For example, a welding process where the primary concern of interest to engineers is the strength of the weld and the variation in the weld strength values. Through scientific experimentation, the factors that affect the mean weld strength and variation, can be determined. Through experimentation, one can also predict the weld strength under various conditions that come from the welding machine parameters or factors. (Jiju 2003)

To successfully apply industrial DOE process, the following skills are needed: planning skills, statistical skills, teamwork skills. Most importantly a successful process requires a good knowledge of the process under experimentation. It is important to understand all factors that can affect the outcome of a process. Without a clear understanding of the process and the factors that matter, it is very possible to draw statistically correct, but physically irrelevant conclusions. (Jiju 2003, Davim 2012)

Some factors can usually be controlled rather easily. However, there can be others that can't be controlled with reasonable effort or cost. Picture 1 portrays how the output of a process is dependent on the input and other factors (Jiju 2003, Davim 2012)



Picture 1: Contributing factors to process output (Jiju 2003, Davim 2012)

In picture 1, the outputs represent the measurable result of the process. Controllable variables are relatively easily controlled and they have a significant impact on the output of the process. Uncontrollable variables can't be controlled easily. They can cause the results of a process to be inconsistent and may be a reason for poor performance of a product. Usually the controllable and uncontrollable variables have a strong relation. Therefore a system design should be made in a way that the controllable variables cause the uncontrollable variables to have as small an impact as possible. This can be accomplished only with a good understanding of the process under examination. (Jiju 2003)

2.3 Product lifetime estimations

Binomial distribution can be used when tests being conducted have two options of outcome for each individual test. Binomial distribution basically answers a question yes or no – can a product survive a specified time period without failures? This is why it can be efficiently used to estimate the probability of a product meeting its specified requirements. (Sheldon 2007)

Binomial distribution is thereby well suited for counting the probable lifetimes of products. Using binomial distribution, the lifetime model for a group of products is presented in the following equation. (Sheldon 2007)

$$1 - C = \sum_{i=0}^{f} \frac{n!}{i!\,(n-i)!} (1-R)^i R^{(n-i)}$$

In which

C = confidence level ($0 \leq C \leq 1$)
f = number of failures allowed
n = number of samples tested
R = reliability ($0 \leq R \leq 1$)

If no failures are allowed the equations becomes simple. This case is presented in the next equation.

➔ When f = 0

$$1 - C = R^n$$

➔ From this formula all the variables can be solved.

$$C = 1 - R^n$$

$$n = \frac{\ln(1-C)}{\ln R}$$

$$R = (1-C)^{\frac{1}{n}}$$

If one failure does occur during the tests, the equation transforms into the following.

➔ When f = 1

$$1 - C = R^n + n(1-R)R^{n-1}$$

The presented equations apply when we test the system for a desired lifetime with the same amount of test cycles used. We can also reduce the amount of test cycles needed by testing the desired value with a greater number of test cycles. The next equation has this taken into account.

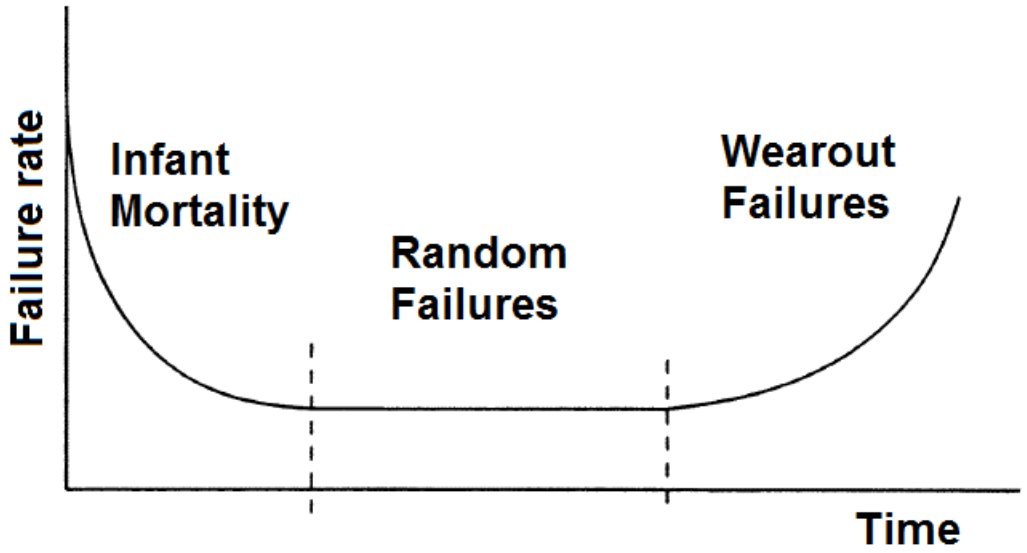
$$n = \frac{\ln(1-C)}{\ln R} \left(\frac{L_T}{L_D}\right)^{\beta}$$

Where

L_T = Tested lifetime
L_D = Desired lifetime
β = Constant

These equations can be used, for example, to calculate the sample size needed to reach a specific confidence level with a set reliability. If more failures occur, the equations need to be recalculated. These equations are useful when a system's reliability is tested for certain types of failure. If a failure does take place, but it's of another sort, these equations still apply for the original test case. It must be noted, that in complex systems it can be hard to say if the failure types could be related in some way. For the presented calculations to yield the true confidence level, this eventuality must be ruled out.

It has been suggested that a bathtub curve is a good way to estimate the frequency of failures during a products lifetime. A bath tub curve is presented in picture 2.



Picture 2: Bathtub curve (Klutke 2003)

Bathtub curve has been found to often represent the way failures occur during a product's lifetime. A bathtub curve is a theoretical model that has often been claimed to apply. If the theory is correct, during the early burn-in period, failures are relatively frequent. If the product works, it is likely to do so until the parts start to fail. Once the early stage has been passed, there are few failures that are random by nature. Towards the end of a products life cycle, parts are getting so worn that failures again begin to be more likely. A bath tub curve has considerable importance in reliability practices and it does seem to accurately predict likelihood of failures in some situations. (Klutke 2003)

3 LEAN - philosophy

Lean philosophy aims to maximize the value of processes by minimizing all waste in the value chain. Lean gives companies competitive advantage by freeing both time and money on doing the right things. In lean philosophy, all that doesn't directly create value for the customer is considered waste and all such waste should be removed. (Kouri 2009, Chiarini 2013, Rother & Harris 2001)

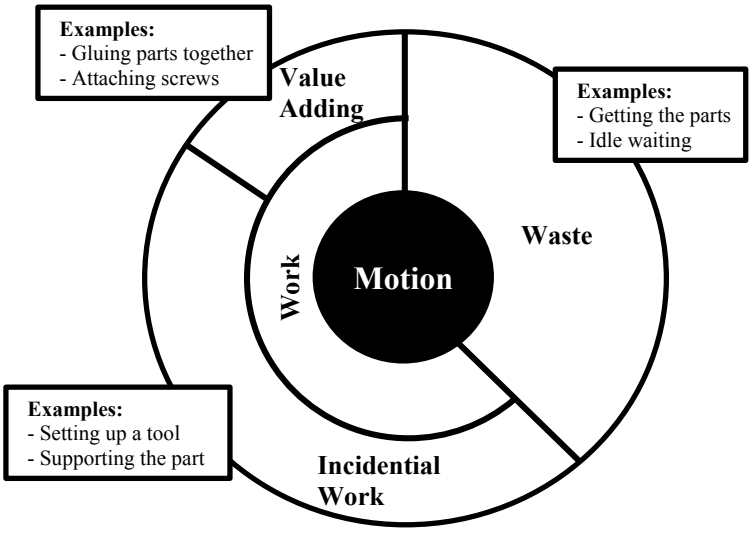
3.1 Waste in processes

Lean production philosophy traditionally recognizes seven different types of waste that can be found in processes (Kouri 2009, Chiarini 2013):

1. **Overproduction** means producing more than is required to fulfill the current demand. This always leads to other sorts of waste appearing in the process.
2. **Waiting** does not create any value to the customer, while costing a lot for the manufacturing company. Some of the possible causes for this waste are machines being broken or delays in the material flow.
3. **Transportation** does not add value. All moving of materials should be reduced to the bare minimum required for the production.
4. **Defects** waste materials and capacity. If they are not spotted and eliminated before delivery, they also cause unsatisfied customers.
5. **Inventory** binds capital and doesn't benefit the customer. Inventory also increases the lead time and can hide other problems in the process.
6. **Over-processing** means all the processing that doesn't increase the products value for the customer. This can for example mean an unnecessarily fine surface quality.
7. **Motion** does not add any value to the product.

Nowadays an 8th type of waste is also recognized. This is the unused creativity of a worker. Idea being, that workers have the best knowledge as to how the processes are actually being conducted. Thereby workers also know how the work could be made easier and more efficient. (Kouri 2009, Chiarini 2013)

Picture 3 below presents one possible distribution of work and waste. It is not uncommon that an operator's time consists of little actual value adding work. Other parts are incidental work that makes the value adding work possible. This work is necessary, but should be designed to be as easy as possible. Usually there is also a certain amount of complete waste that could be removed or at least reduced greatly by putting all parts and tools close at hand. (Rother & Harris 2001)



Picture 3: Value adding and other processing (Rother & Harris 2001)

Distribution of the operators work time is often a large issue, but it is usually not the worst one. The single biggest problem manufacturing and service industries have to fight is overproduction. Overproduction simply means producing an amount of products that exceed the demand. What makes overproduction the worst of the waste types is that it leads to other problems, such as (Chiarini 2013, Rother & Harris 2001):

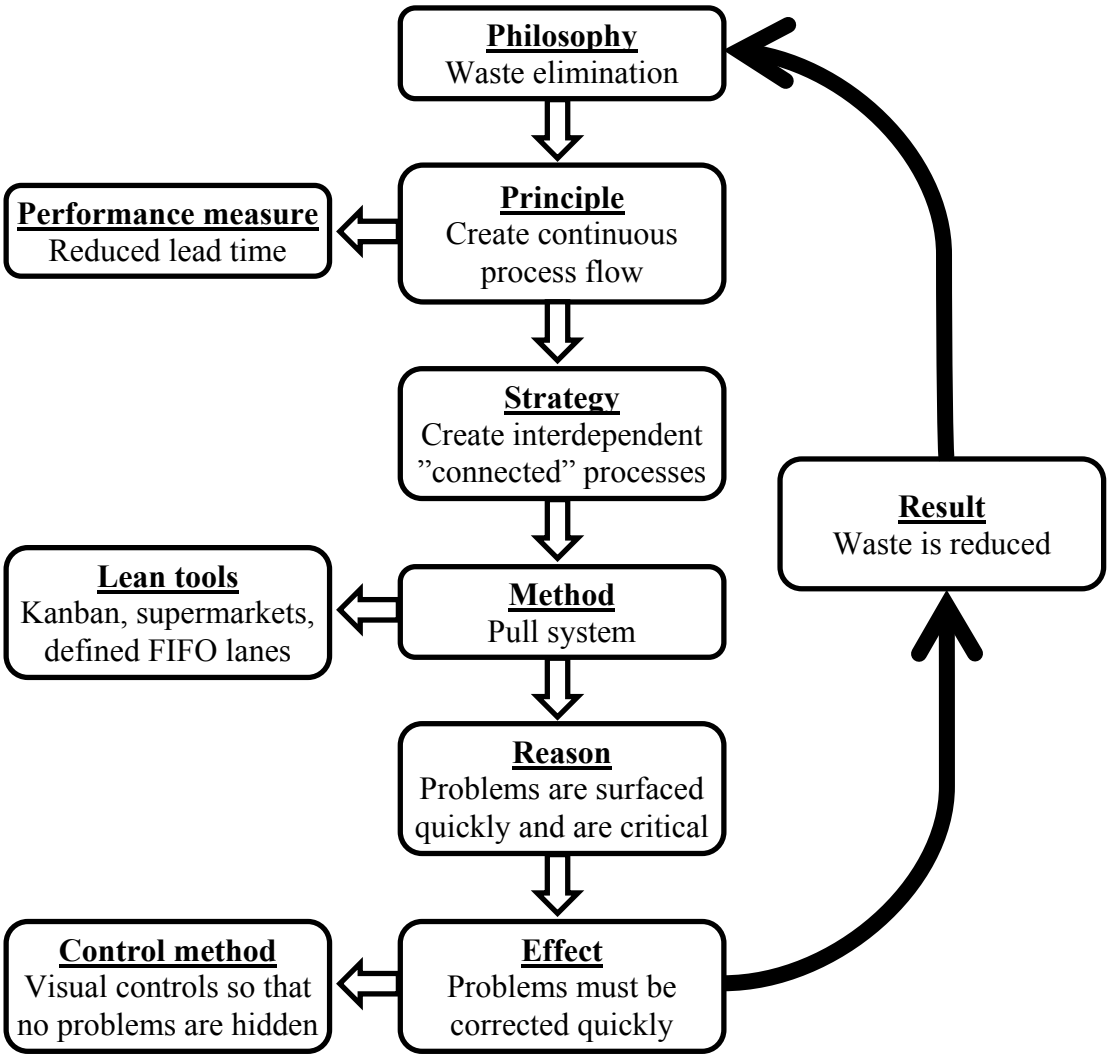
- Increase in inventories
- The production process slowing down
- Reduction of planning flexibility
- Increase of indirect cost such as transport, inspection, etc.

Overproduction is never a singular issue, but it always causes problems in other parts of the value chain. Best way to prevent overproduction is to understand the reasons behind it and work on removing those from the process. The reasons leading to overproduction are often linked to (Chiarini 2013, Liker & Meyer 2006):

- Production of oversized “economical” lots
- Producing before or after demand
- Low speed of setups
- Creating inventories to make up for defected products
- Too many people in the process
- Too many or too fast machines

When people on all levels of an organization are aware of the ways waste can manifest and the ways it can harm the company, removing it becomes much easier. When waste has been identified, it can be removed. Process-mapping tools have been developed for identifying waste. One commonly used is value stream mapping (VSM). Value stream mapping is a powerful tool when the operating company is truly wants to identify and remove waste. (Arcidiacono 2012, Chiarini 2013)

Toyota uses a waste reduction model that brings out problems immediately. This is accomplished by using one-piece-flow. When there are no mid-production buffers, all the problems demand immediate attention. If a disturbance does occur, it stops the entire production line. Picture 4 illustrates this model. (Liker & Meyer 2006)



Picture 4: Waste reduction model (Liker & Meyer 2006)

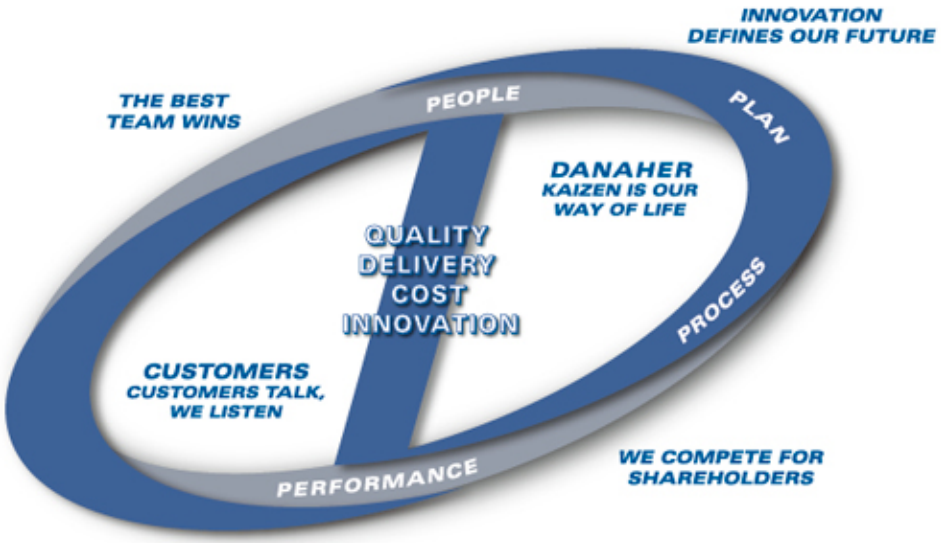
Identifying waste is the first step towards a lean organization. Next comes removing the waste. This is usually more of a challenge as it often takes commitment from a large group of people. By nature, people are reluctant to change the way they do things. Often a proposal for change can be taken as criticism. Everyone has their own opinions as to why things are the way they are. To accomplish a positive and permanent change, all those participating need to understand why change is required and why they should be willing to work towards this common goal. When all those concerned with a change believe in the common goal, it is far easier to achieve. (Chiarini 2013, Shook 2008)

3.2 DBS – Danaher Business System

The Danaher Business System is Danaher Corporation's own adaptation of the lean philosophy. DBS drives every aspect of Danaher's culture and performance. The system is a guide for planning processes and a tool measuring the level of execution.

DBS is built around the five core values of Danaher. The core values are presented in picture 5. The values are (Danaher 2014):

- "The best team wins"
  - Associates are the most valued assets.
  - Danaher is passionate about retaining, developing and recruiting the best talent available.
  - Success comes with team-oriented involvement by all. Solutions have to be based on facts and solve the root causes.
- "Innovation defines our future"
  - Creativity is continuously applied to new technologies.
  - Out-of-the-box ideas add value to the enterprise.
  - "Breakthroughs" are accomplished through PD process.
- "Customers talk, we listen"
  - Quality always comes first.
  - Strategic plan is based on VOC.
  - Robust, repeatable processes yield superior quality, delivery and cost.
- "Continuous improvement (Kaizen) is our way of life"
  - DBS provides tools for continuous improvement.
  - Waste is continuously eliminated from all processes.
- "We compete for shareholders"
  - Financial success enables investing back into the business.
  - Profits are important for attracting loyal shareholders.



Picture 5: Values of Danaher

The system aims to give all Danaher owned companies competitive advantage through clearly specified processes. These processes have been proven to work in removing waste and thereby improving productivity and profitability. (Danaher 2014)

DBS includes many practical tools for process improvement. Danaher has developed its' own versions and instructions for implementing many commonly known lean tools such as PDCA, VSM, SW, etc. Danaher is well known for its successful implementation of DBS across the organization. The practical tools provided for the operating companies make waste removal and problem solving a predefined process that is easily followed. Using DBS has made Danaher an extremely successful company that keeps on growing while further developing the system to keep ahead of the competitors. (Danaher 2014)

3.3 Standard work

Standard work is an important part of a lean process. Objective of standard work is to make the most of human resources, material, and machinery. Standard work is also a great tool for ensuring continuous and stable quality of goods manufactured. Standard work is characterized by three main elements: Takt Time; Standard Work in process and Work sequence. (Arcidiacono 2012, Liker & Meyer 2006)

Using standard work enables the company to always know exactly how much work goes into manufacturing a certain product or product mix, thereby knowing the exact available capacity with the resources at hand. Not knowing can lead to selling more products than can actually be made on time, or refusing new orders in fear of not being able to fulfill the orders. Usual case is the first one, which leads to late deliveries, unsatisfied customers and possible fines. (Arcidiacono 2012)

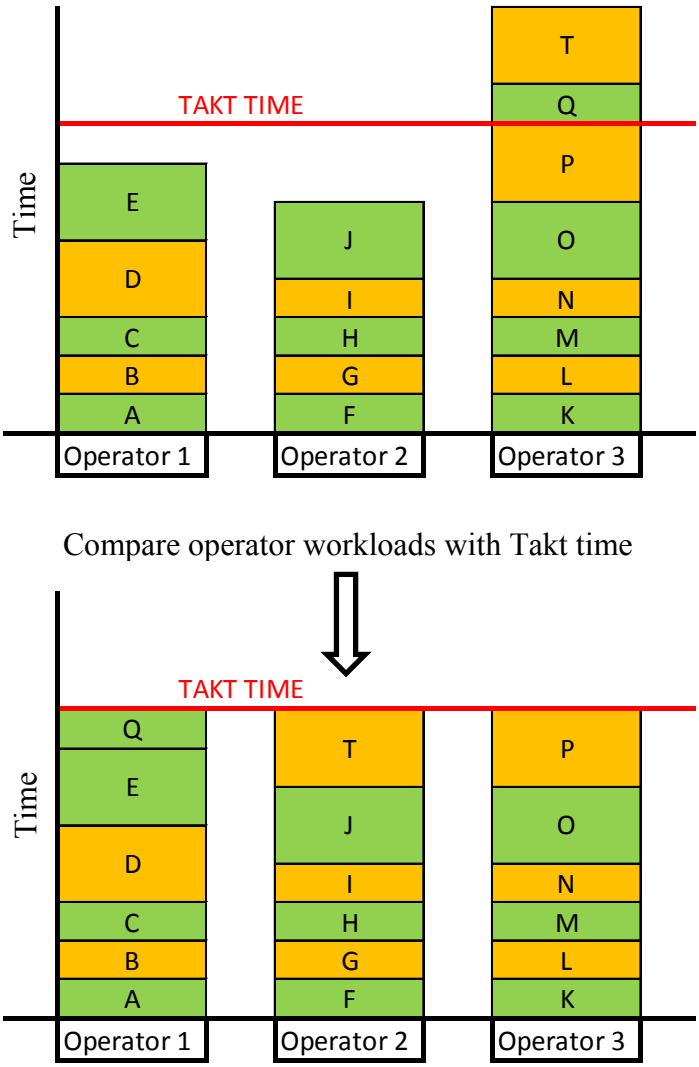
Standard work means optimizing the process to be run at a certain way every time regardless of the person doing the work. Standard work in process means the minimum WIP needed to maintain standard work. Standard WIP can be parts completed and remaining in a machine after auto cycle, parts placed in equipment with cycle bigger than takt time, and parts handled by operators on the production line**.** Standard work sequence is the second part of standard work and means the sequence of steps and activities that need to be performed in order to complete the production process. The third part of standard work, takt time, is closer examined under Heijunka chapter. (Arcidiacono 2012, Liker & Meyer 2006)

To successfully establish standard work, the following things need to be completed (Arcidiacono 2012):

1. Operator cycle time is analyzed
2. The amount of operators needed to meet takt time is defined
3. Machining capacity is measured
4. Interaction between operator and equipment is analyzed
5. Operator workload needs are mapped and compared to takt time
6. Standard work sequence is designed according to takt time
7. Work load is balanced according to customer demand

When processes are timed, especially for the first time, it usually shows that the workloads between operators are not in balance. This can mean that one operator is fully em-

ployed and still can't finish the given work on time, while another operator may have slack time. The slack may not even show as the operator may simply do the work a bit slower. This isn't because of laziness, but cause there is no reason to hurry. The picture 6 presents usual workload balancing process after timing has shown the work being off balance.



Picture 6: Balancing workloads (Arcidiacono 2012)

Establishing standard work can be challenging when people have been allowed to establish their own ways of doing things. If there is no clear way of showing that one way is better than another, people will most likely think that they should not be the ones to change the way they operate. (Arcidiacono 2012, Shook 2008)

Even if standardizing work isn't easy, it should be striven for. When all work is done in a standard manner, it is easy to estimate how many operators are needed to finish a certain amount of products in a set period of time. Quality has been shown to improve with standard work and all issues are more visible. (Arcidiacono 2012)

3.4 Heijunka – production balancing

Heijunka means the concept of production levelling. It is a part of the Toyota Production System (TPS). Heijunka aims to reduce variance of upstream material requirements and of workload utilization. When using Heijunka control, the fluctuation of external demand has to be compensated by the fill time and/or inventory of finished products and/or reserve capacity. Inventory is usually controlled using Kanban. (Klatte & Lüthi & Schmedders 2011, Liker & Meier 2006)

Pull control is an important part of TPS. However, pull control in its pure form leads to fluctuating production following the fluctuating market demand. Consequently, manpower and material requirements vary as well, latter being further aggravated by bullwhip effect. Bullwhip effect means that the fluctuations in demand cause greater fluctuations in inventory value when going up the supply chain. As a countermeasure, TPS recommends Heijunka, that is production levelling at the last production stage in order to filter out short-term demand variation. (Emmanouilidis 2012, Klatte & Lüthi & Schmedders 2011, Liker & Meier 2006)

In a multi-product environment, Heijunka fixes a schedule for one day or one week. The schedule is composed of small production lots, ideally one piece at a time. The intervals between consecutive lots are planned to be as even as possible and the allocated capacity is sufficient for at least the average demand. (Klatte & Lüthi & Schmedders 2011)

In order to produce only the products the customers need, the supplier has to adapt its production process to the customer orders and produce takt time. Takt time is used to synchronize the pace of production with the pace of sales. It is calculated by dividing the available working time per day by the customer demand rate per day. The formula for calculating takt time is presented below. (Matzka et al. 2009, Liker & Meyer 2006)

$$takt\ time = \frac{available\ working\ time\ per\ day}{customer\ demand\ rate\ per\ day}$$

This formula gives the time interval in which product needs to be produced. Simultaneously it sets the time limit for each step of the process leading to the final product. If the process time of one step can't meet the takt time, the process can't meet the takt time. By comparing process times to takt time it is possible to estimate the production line's ability to meet customer demand. (Rother & Harris 2001)

Takt time can be used to estimate the amount of operators needed to run a production cell. This is done by first performing a paper kaizen to evaluate the total work content of a production cell. When the total work content is known, it is compared to the takt time according to the equation presented below. (Rother & Harris 2001)

$$\frac{total\ work\ content}{takt\ time} = number\ of\ operators$$

Often the result of this equation is not even. Instead the result may suggest using some tenths of an operator to run the cell. An example of such an event is presented below. (Rother & Harris 2001)

$$\frac{79\ seconds\ of\ work\ content}{35\ second\ takt\ time} = 2.26\ operators$$

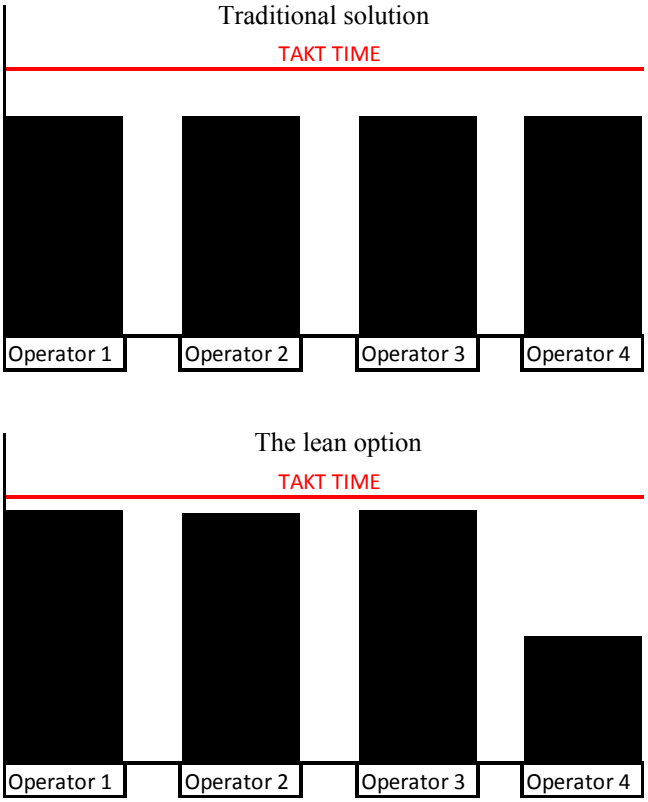
Without any further improvement to the process, the cell in question would require three operators to run. However, the result isn't far above two. This means that using three operators would result in low productivity. The cell could be run with two operators if the production team is willing to set this as a shared goal. Table 1 below provides a guideline to evaluate the required amount of operators. The table is made with the assumption that operator loading will be in the 90 % to 95 % range. This means that 90 % to 95 % of each takt interval is filled with work. (Rother & Harris 2001)

Table 1: Guidelines for determining the number of operators in a cell (Rother & Harris 2001)

Remainder in # of operators calculation	Guideline / Target
< .3	Do not add an extra operator. Further reduce waste and incidental work.
.3 < x < .5	Do not add an extra operator yet. After two weeks of cell operation & kaizen, carefully evaluate if enough waste and incidental work can be taken out.
> .5	Add an extra operator if necessary and keep reducing waste and incidental work to eventually eliminate the need for that operator in the cell.

When a company runs at the upper range of this suggested operator count guideline, it has to face a choice of how to distribute a less-than-full work content among the operators. Traditionally an attempt is made to evenly distribute the work content between all operators. While this approach is "fair", it also makes it harder to eliminate waste later and creates the potential for over production. This is because the traditional balancing usually wind up working as "isolated islands". This leads to small batches of inventory piling up between operators. (Rother & Harris 2001)

A better option for distributing the workload is to fill all but one operator with work elements consuming almost the entire takt interval. When all the waste of waiting is piled on one operator, the opportunity for improvement through kaizen is more visible. Differences between the traditional balancing and the lean option are presented in the table below. (Rother & Harris 2001)

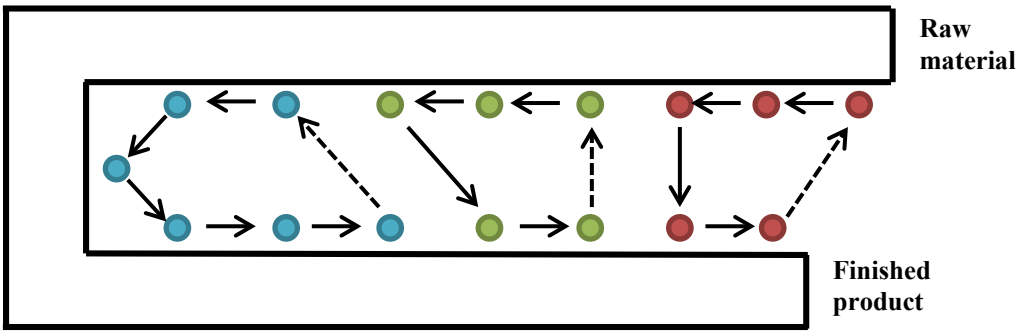


Picture 7: Traditional production balancing vs the lean option

In picture 7, the traditional production balancing option is presented on the top and on the bottom the lean option. The lean option balances all but one of the operators' workloads, so that the waste is brought to surface. (Rother & Harris 2001)

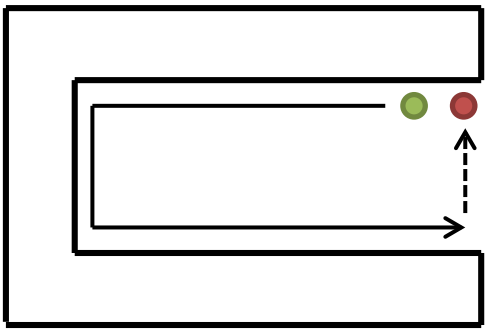
There are different types of basic approaches for distributing the workload among the operators. Following list comprises of some basic approaches to production balancing. After each of the approaches, there is a picture to illustrate how the concept would actually work. The operators are presented as circles of different colors. Arrows show the operator movements between tasks. Dotted arrow presents the movement back to the beginning. (Rother & Harris 2001)

1. **Split the work** among the operators so each performs one takt time worth of the total work content, often moving between several machines. The model is illustrated in picture 8.



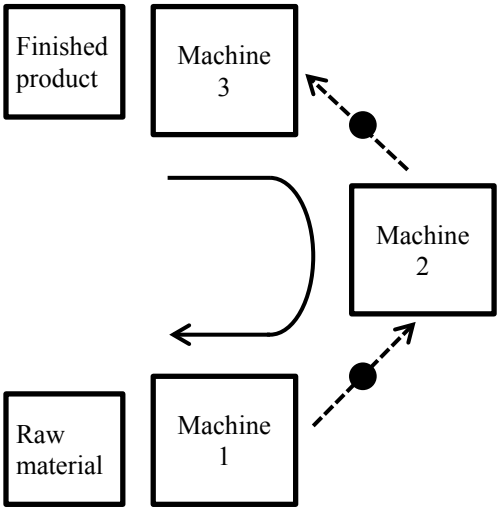
Picture 8: Split the work

2. **The circuit,** where one operator performs all the work elements to make a complete circuit of the cell in the direction of material flow. A second operator follows a few stations behind. The model is illustrated in picture 9.



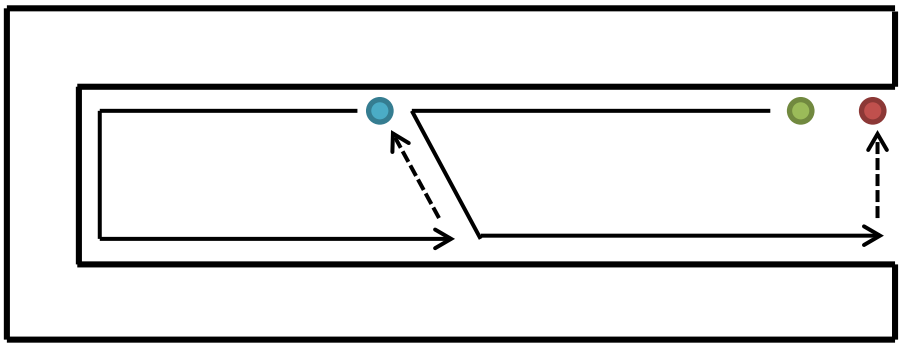
Picture 9: The circuit

3. **Reverse flow,** in which the operators make a circuit in the reverse direction of the material flow. The model is illustrated in picture 10. In this picture the operator movement is a continuous arrow, while material flow is presented as a dotted arrow. Material holding positions are presented as a black circles.



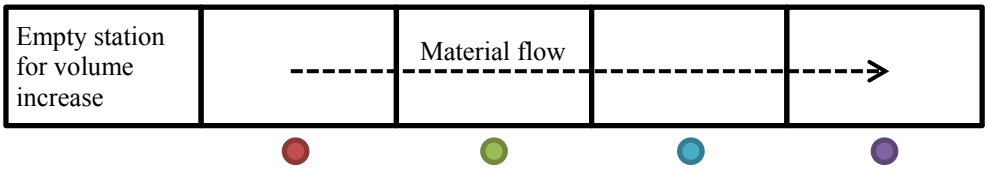
Picture 10: Reverse flow

4. **Combinations** of splitting the work and a circuit or reverse flow is illustrated in picture 11.



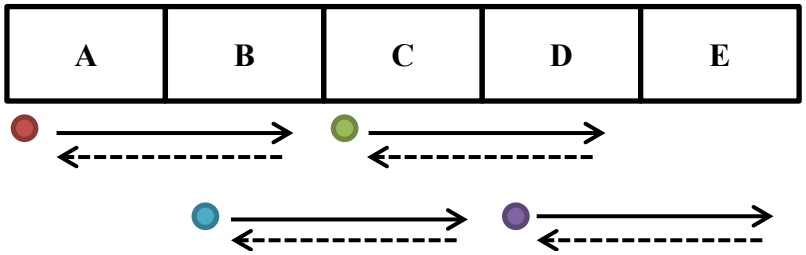
Picture 11: Combinations

5. **One operator per station,** in which each operator stays at one workstation, is illustrated in picture 12.



Picture 12: One operator per station

6. **The ratchet,** in which each operator works two machines and "ratchets" the work piece ahead each time the operator moves to a downstream machine, is illustrated in picture 13.



Picture 13: The rachet

It needs to be noted that not all of these workflow models work in all situations. The presented models have been shown to work in some situations. How the operators should move and how the work should ultimately be split depends on takt time. (Rother & Harris 2001)

Creating a perfectly flowing process would demand a completely even customer demand. As this is not realistic, the production will have to be able to react to fluctuations in the demand. Adjusting the production to every frequently manifesting twitch in demand would run up production costs and make quality fall. Also, it is not realistic to expect the same mix of products to be demanded constantly. Changeover between different products can cost a lot of time. (Liker & Meyer 2006)

Alternative is to produce large batches of products to minimize the effect of changeovers. The cost of this approach is that the response time to new customer orders would increase along with capital tied to stock of both finished and unfinished products. Maintaining flow is thereby the better option for the sake of efficient use of capital, quality, on-time-delivery and consequently customer satisfaction. (Liker & Meyer 2006, Rother & Harris 2001)

3.5 5S – visualization tool

Principle of lean is that productive and quality producing work can only occur in a clean environment. 5S is a practical tool for improving and sustaining cleanliness and order in a production environment. 5S helps to create a standardized and disciplined working environment. According to lean philosophy effective processes can only appear in a clean environment where waste is easily spotted. (Kouri 2009)

Implementing 5S has several benefits. The program increases safety of the working environment. 5S maintains order of the workstation and thereby reduces frustration and waste of time caused by searching of tools. Production work is made easier by carefully planned location of tools and materials. Cleanliness and precision support forming of lean culture. 5S also improves the control of equipment used in production. (Kouri 2009, Liker & Meyer 2006)

The term 5S originates from to following five Japanese words (Stevenson 2009, Osada 1991):

- Seiri: sort necessities and remove unnecessary objects.
- Seiton: arrange and clearly mark places for everything necessary.
- Seiso: clean and maintain machines and equipment.
- Seiketsu: standardize procedures.
- Shitsuke: maintain the above mentioned stages.

Seiri means that all objects at a work cell are to be divided to necessary and unnecessary. Only the objects that are absolutely needed for the work are left at the cell. All other objects should be removed. Something that may be needed occasionally should also be removed and stored for when it's actually needed. If there are objects that are never needed, they should be scrapped or sold. Keeping just the necessities at the work station frees up space and makes the required object more accessible. (Stevenson 2009, Osada 1991)

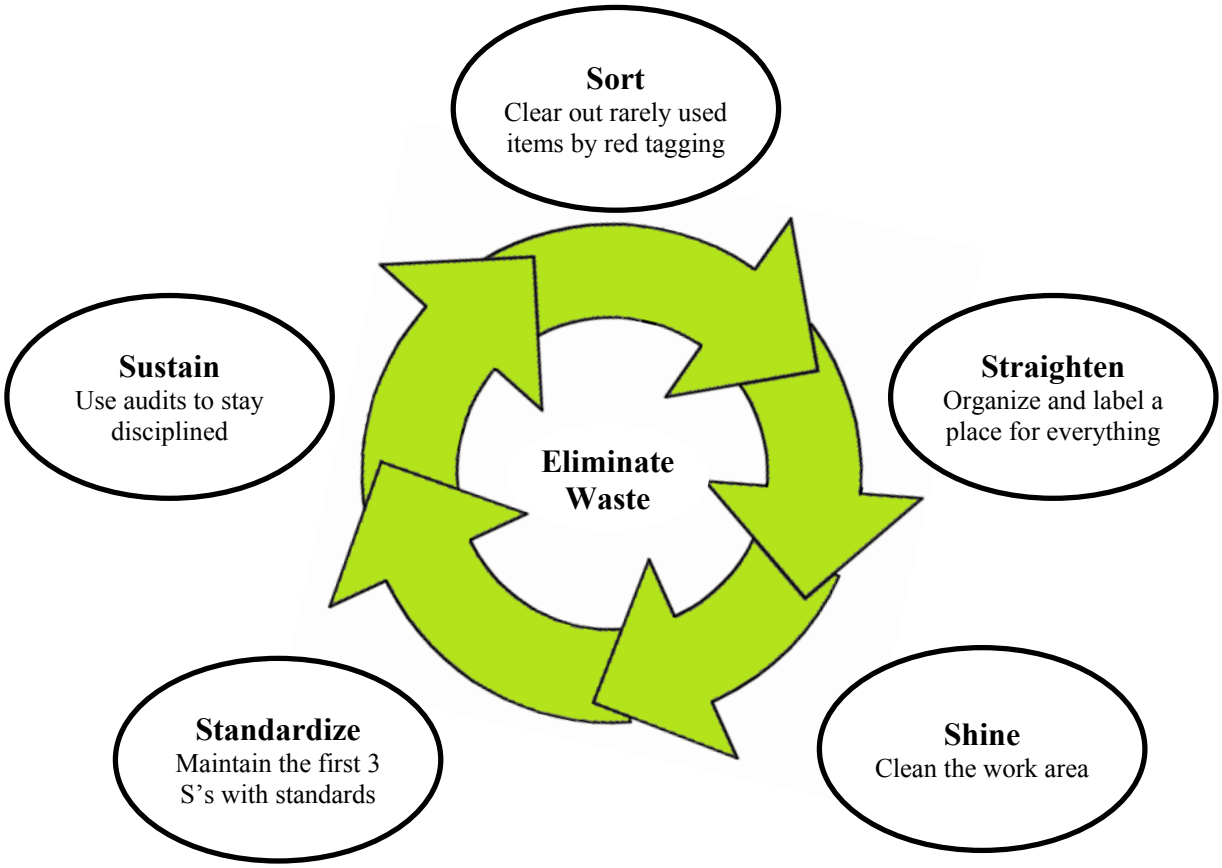
Seiton mans that the objects that remain at the work station should be organized. All the tools and parts should be placed right where they are needed. The objects should also be marked so that their purpose is obvious and so they always find their right position. These actions make work more efficient as the worker doesn't spend time searching for out of place parts and tools. (Stevenson 2009, Osada 1991)

Seiso means keeping to working station clean. This should be a continuous action that is done on regular basis. Cleaning should not only be done for special occasions. In addition to looking good, a clean work station makes all irregularities more visible. This way, problems are seen before they cause problems for the process. (Stevenson 2009, Osada 1991)

Seiketsu means standardizing processes that aim to reduce variation in production processes. The idea is to split the work into many simple pieces. This enables the workers to work in the same way and to be able to learn new work fast. (Stevenson 2009, Osada 1991)

Shitsuke means self-discipline and it aims for sustainment of the previous S's. This also means that the process needs to be audited to make sure that all the implemented processes stay in use. This enables building a 5S culture.

English equivalents for these Japanese words are sort, straighten, shine, standardize and sustain. The idea of 5S is presented in picture 14.



Picture 14: The 5S process (Liker & Meyer 2006)

3.6 Kaizen – continuous improvement

Kaizen is a philosophy that originates in Japan. The word kaizen translates to continuous improvement. The idea is to continuously analyze every process/activity and remove obstacles that stand in the way of them working seamlessly. Lean organizations are based on the idea of continuously improving the ways all operations are run. Kaizen gives companies competitive advantage leading to increased performance and financial results. Kaizen requires strong commitment and effort from management and every department. Since the purpose of kaizen is to continuously improve, there is no final destination. To properly do kaizen is to not stopping to celebrate the results achieved, but to keep searching for ways to further improve. (Imai 1986)

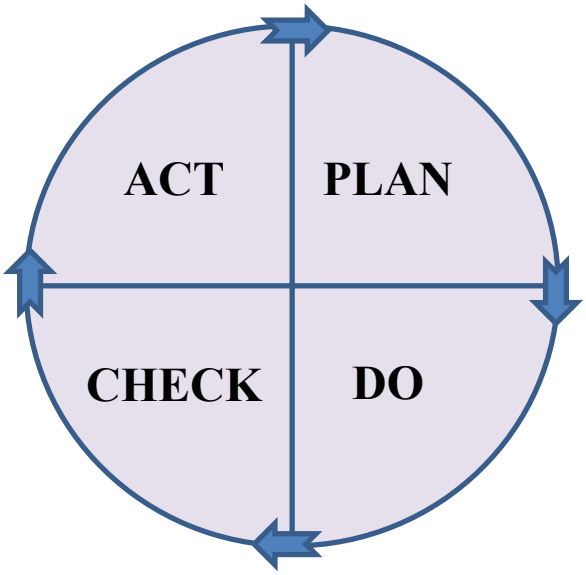
Lean organizations often run so called kaizen workshops or kaizen events. The purpose of these projects is to achieve improvement by gathering up a specific team to solve problems related to some process. Depending on the targets set for the kaizen at hand, the teams usually fall in one of the following two categories (Chiarini 2013):

- Teams that focus on reducing waste and especially on reducing value stream lead time.
- Teams that focus on reducing variance in processes and on improving quality.

DMAIC is a method used in Six Sigma production philosophy for continuous improvement. The method defines the steps that need to be taken to achieve improvement. The acronym DMAIC is composed of the words define, measure, analyze, improve and control. More specifically the DMAIC steps are (Chiarini 2013):

- Define: determining the processes that require improvement, while being in agreement with the company's strategies and CTQs of these processes; at this stage the team that will carry out the project is assembled, the deadline and the goal in terms of saving are defined;
- Measure: measuring the current state of CTQs and assessing the deviation from the target;
- Analyze: determining the reason why the target is not being reached and thus create defects and waste (Muda in Lean);
- Improve: launching improvement projects to remove the causes of nonconformity and waste (Muda).
- Control: measuring the improvements, certifying the economic and financial savings and developing a standard method to continue improvement.

A very similar tool for continuous improvement is the PDCA cycle. The acronym comes from the words plan, do, check and act. The model is illustrated in picture 15.



Picture 15: PDCA cycle

The most important part of kaizen is creating a culture that supports it. Without a culture where people are truly persistent to do kaizen, no major result can be achieved. Therefor it is crucial to get people excited to continuously improve. (Imai 1986)

3.7 TPM – total productive maintenance

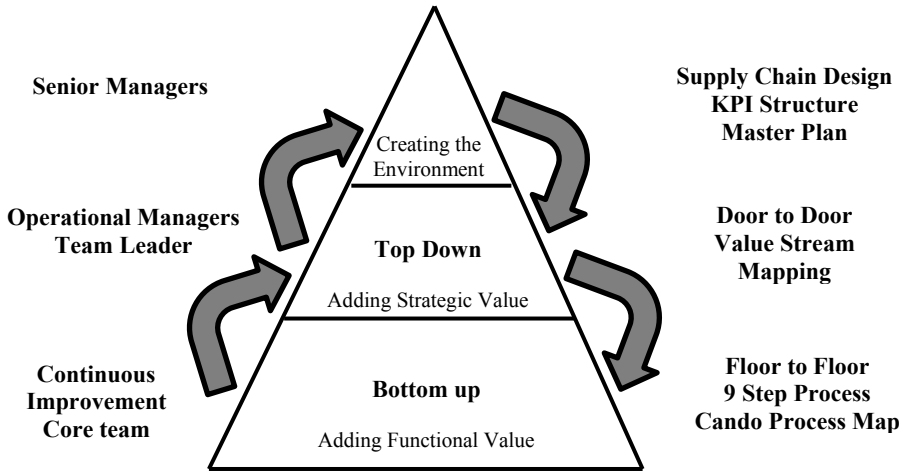
TPM stands for total productive maintenance or total preventative maintenance, depending on the source. The meaning of the concept is still the same. The purpose of TPM is to maximize the productive work time by estimating and preventing machine breakdowns. This is done by scheduled maintenance procedures. Implementing TPM has several advantages (Chiarini 2013, McCarthy & Rich, 2009):

- **Productivity** is increased by reducing downtime of productions machines. Consequently non-value-adding work is reduced.
- **Quality** is improved since control of equipment quality increases the possibility that the products made are within given tolerances.
- **Cost** of operations is reduced due to less material required for spares.
- **Delivery** on time increases due to reduced amount of unpredicted downtime. This also leads to shorter lead times and faster conversion processes.
- **Safety** is improved by reducing amount of unplanned events. Consequently there is also less movement and abnormal conditions become visible easily.
- **Morale** is improved by increasing the understanding of the technology in use and by having more time to manage the necessary maintenance processes.
- **Environment** is better taken care of with closer control of the equipment in use and less unplanned events.

The idea was first introduced to Japan in the 1950s when it arrived from the US. The Japanese identified five critical factors for getting benefit from TPM. These five factors were (McCarthy & Rich 2009):

- Maximizing equipment effectiveness
- Planning a maintenance system for the entire lifetime of equipment
- Having all departments involved in TPM, if they plan, design or use equipment
- Involving all employees at every organizational level
- Motivating people to TPM with group activities

Maintenance process is controlled by TPM master plan that comes from the organizational leadership. The plan is used to coordinate learning across the entire company and to get focus on delivering the business goals. It is aiming to create a culture that supports TPM. The organizational roles of people at different levels of the organization is presented in picture 16. In TPM it was recognized that bringing the operators into the process created culture that supports 5S and motivates the operators. (McCarthy & Rich 2009)



Picture 16: The organizational structure of TPM

Involving people at all organizational levels was seen as an efficient way to create understanding towards the equipment used by the company. What TPM brought to light was that all equipment failures were due to physical phenomena that can be identified. By identifying the cause of the failures, they could be reduced or in some cases even eliminated. The following six categories of equipment lost were recognized (McCarthy & Rich 2009):

- Breakdowns cause by failed equipment
- Unnecessary set ups and adjustments
- Idle processes
- Reduced process speed
- Losses due to start up
- Need for rework and scrapping

The main reasons for these failures were found to be:

- Poor condition of equipment
- Human error or lack of motivation
- No understanding over how the optimum conditions can be achieved

By using these findings it was recognized that all breakdowns could be avoided. This could be achieved by creating a system that follows and sustains equipment condition and makes it possible to identify potential failures before they occur. The system should also include minimizing the chance of human errors. The system suggested that breakdowns should never be accepted as inevitable, because this reinforces a working pattern that leads to failures. Aiming for zero breakdowns of equipment thereby creates a better result than considering some failures to be unavoidable. (McCarthy & Rich 2009)

3.8 JIT production using Kanban

Just In Time –production (JIT) aims to minimize production costs by reducing waste in production. JIT –production drives towards one piece flow and flawless co-operation of different production processes throughout the whole production process. Autonomy of quality control in different production stages is required to ensure that flawed products do not enter the next stage of production. JIT –process has been found to be a practical way to reduce stock, to recognize and remove waste, and to systematically improve competitiveness of a company. Standard work, cross training and work safety are necessities to get the full potential out of JIT –production. (Zandin 2001)

Kanban is one of the most used tools for JIT –production. It is a powerful tool for preventing overproduction by setting the amount of products that are allowed to be made. Kanban has the following benefits (Chiarini 2013):

- No overproduction
- Improved flexibility
- Smaller lots produced at a time
- Simple to use and understand
- Process can be unified all the way from the supplier to the customer

There are traditionally two types of kanban (Chiarini 2013):

- Transportation or movement kanban
- Production kanban

Transportation kanban makes items move to the next process. The kanban can be further divided into two groups: supplier kanban works as on order to supplier, while internal kanban is used to control internal materials within the plant. Production kanban is simply a permission to produce the next product or batch of products. (Chiarini 2013)

The working principle of kanban is that it "pulls" items at the rate they are needed. In a perfectly flowing system, the kanban would be zero as there would be no buffers between processes. This would require the takt times of each process to be exactly the same, so it is almost impossible to achieve. In practice, downstream processes pull products from the upstream process by using kanban labels. Upstream processes only produce more when they receive a kanban order. (Chiarini 2013)

Kanban is widely used because of its simplicity and effectiveness. Usage of kanban has been shown to efficiently prevent overproduction and thereby free capital by reducing unnecessary inventory. (Chiarini 2013)

3.9 TOC – Theory of constraints

The theory of constraints is a manufacturing philosophy on understanding the manufacturing processes and identifying its constraints. A constraint is considered to be anything that limits a system from performing better or meeting goals. (Halevi 2001)

According to TOC, few resources in the manufacturing process need a detailed schedule. Material is supposed to flow in small batches. The required amount of units to be processed with one setup may be larger than transfer batches. This means that simultaneous processing by non-constraints is acceptable. A non-constraint process is allowed to be inefficient up to a point. When released, material quickly flows to the constraints. Non-constraint resources tend not to accumulate inventory. If queues at non-constraints are short or non-existent, the order of work is trivial. Non-constraints work solely to make sure that the constraints have work all the time. This makes traditional capacity management techniques, which aim to optimize local performance of every resource, obsolete. TOC process steps are (Halevi 2001):

1. Identify system constraints.
2. Decide how the system constraints are used.
3. Support that plan with all other actions.
4. Elevate the system constraints.
5. Go back to step one if any of the earlier steps are broken.

Major constraints that any system has to take into account are market demand and capacity. Usually factories have only few capacity constraints. Drum buffer rope is an approach that sets the rate of production in the entire factory according to these constraints. Buffers should not be built higher than the policy dictates as this is only waste of money and increases the throughput time while reducing on-time delivery. Negative significance of constraints can be reduced by investing in more machines or having the constraints be worked in longer shifts than non-constraints. (Halevi 2001)

While executing the TOC process it is important to keep re-evaluating the current situation. This is to make sure that no problems arise from old policies that were made in different circumstances. (Halevi 2001)

Drum buffer rope (DBR), production scheduling technique, was developed for practical implementation of TOC. Name of the technique comes from a metaphor, in which drum signifies the constraint that determines the pace of production. Material is pulled to the first operation, by the rope, at the pace determined by the constraint. Buffer is the fixed time that material waits before the constraint. Constant buffer at the constraint is ensured by this fixed time between material releases. (Halevi 2001)

By using DBR it is then possible to create flow to production while maintaining a predetermined level of inventory. By setting the pace according to the constraint, it is possible to reach high utilization at the constraint. It is only necessary to keep a determined buffer at the constraint and nowhere else. Keeping more buffers increases value of inventory and can reduce throughput. (Halevi 2001)

4 VACUUM TECHNOLOGY

In a "good" vacuum there is a long mean free path for collision between the vaporization source and the substrate. Also, a good vacuum enables control of the amount of gaseous and vapor contamination during processing. This kind of vacuum environment is generated by a vacuum system that includes the deposition chamber, introduction chambers, vacuum pumping system, exhaust system, gas inlet system, and associated plumbing. (Mattox 1998)

The fixturing and tooling used to hold, position, and move the substrates are also important to the system design. If some materials are cleaned outside the deposition system they may be recontaminated in the system during evacuation by system-related contamination. The film can be contaminated during deposition by system-related contamination and by process-related contamination. Good vacuum system design, construction, operation, and maintenance aim to control these sources of contamination. (Mattox, 1998)

4.1 Gases and vapors

Definition of gas is a state of matter where the atoms and molecules composing the material uniformly fill the container holding the material. Vapor is a gaseous species that can be easily condensed or absorbed on surfaces; for example water vapor. A vapor molecule is often larger than a gas molecule. "For example, water molecule H-O-H has a triangular configuration with an effective molecular diameter of 2.64 Å; this can be compared to a molecular diameter of 2.98 Å for oxygen (O-O) and 2.4 Å for hydrogen (H-H)." (Mattox, 1998)

"Avogadro's number is the number of molecules in a mole[a] of the material and is equal to 6.023×10^{23}. Under "standard temperature and pressure" (STP) conditions of 0 °C and 760 Torr, a mole of gas occupies 22.4 liters of volume. In a standard cubic centimeter (scc) of a gas, there are 2.69×10^{19} molecules." (Mattox, 1998)

In a vacuum condition the gas pressure in a container is less than that of the ambient pressure. The difference in pressure does not need to be great. It can, for example, be as small as the pressure used to control gas flow in a system. The pressure difference can also be large, such as that used in vacuum-based PVD systems. The large pressure difference is to give a long mean free path for vaporized particles and to allow the control of gaseous and vapor contamination to any desired level. A vacuum is considered "rough" when there is little pressure difference between the vacuum and the atmosphere. This means having a pressure of about 10^{-6} ($>10^{-3}$ Torr) of that of the atmosphere or about 10^{13} molecules/cm^3. Vacuum is considered "good" when it has pressure of about 10^{-9} ($\sim 10^{-6}$Torr) that of the atmosphere or 10^{10} molecules/cm^3. Vacuum is considered very ultrahigh (VUHV) when there are about 10^4 molecules per cubic centimeter and the pressure is 10^{-12} Torr. (Mattox, 1998)

The kinetic energy of gas molecules comes from equation $E_k=1/2mv^2$, where m is the mass and v the velocity. Another way to calculate the kinetic energy of gas is using equation $E_k=3/2kT$, where k is Boltzmann's constant and T is the temperature in degrees Kelvin. These molecules cause a pressure when they hit a surface. Pressure is the

combined force of all particles striking the surface. In the case of mixture of gases, the total pressure will be the sum of partial pressures of the gases or vapors in the mix. (Mattox 1998, O'Hanlon 2005)

4.2 Water vaporization

The residence time of water vapor is appreciable. Because of this, removal of water vapor is dependent on the number of collisions it goes through while escaping the system. As a result of this, it takes a far longer time for water vapor to escape a system, than for example gaseous material such as nitrogen. This is why water vapor is often the dominating contaminant in many vacuum systems. Table 2 presents how water vapor pressure varies in different temperatures. (Mattox 1998)

Table 2: Equilibrium vapor pressure of water (Mattox 1998)

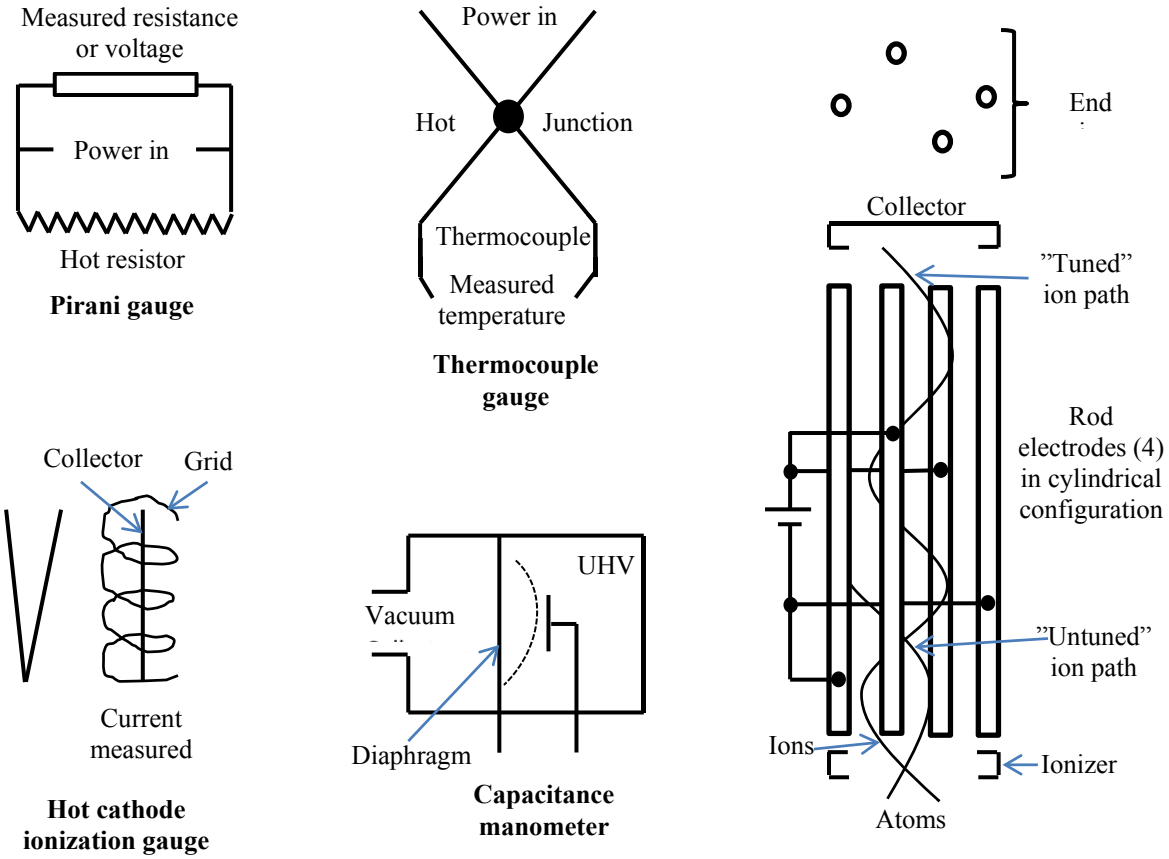
Temperature (°C)	Vapor pressure (Torr)
-183	$1{,}4 \times 10^{-22}$
-100	$1{,}1 \times 10^{-5}$
0	4,58
20	17,54
50	92,5
100	760
250	29 817

Reaching a certain vacuum pressure is far faster when surfaces of the parts in a vacuum are dry to begin with. In order to get rid of moisture on the surfaces it is vacuum pressure should be combined with heat. (Mattox 1998)

4.3 Pressure measurement

By using vacuum gauges, gas pressure can be monitored. This can be done either directly or indirectly. Vacuum gauges are often used to control different aspects of PVD processing. For example, the vacuum output indicates when it's time to cross from roughing to high vacuum pumping and when it's time to start thermal evaporation. There are several ways a gauge can function, including:

- Pressure exerted on a surface with respect to a reference – e.g. support of a column of liquid as in mercury manometer; deflection of a diaphragm as in a capacitance diaphragm gauge (CDG). (Mattox 1998)
- Thermal conductivity of gas – e.g. thermocouple gauge; Pirani gauge, convectron gauge. (Mattox 1998)
- Ionization and collection of ions – e.g. hot cathode ionization gauge; cold cathode ionization gauge; radioactive ionization source gauge. (Mattox 1998)
- Viscosity measurement – e.g. spinning rotor gauge (SRG). (Mattox 1998)
- Ionization with mass analysis and peak-height calibration – e.g. mass spectrometer. (Mattox 1998)



Picture 17: Vacuum Gauge Configurations (Mattox 1998)

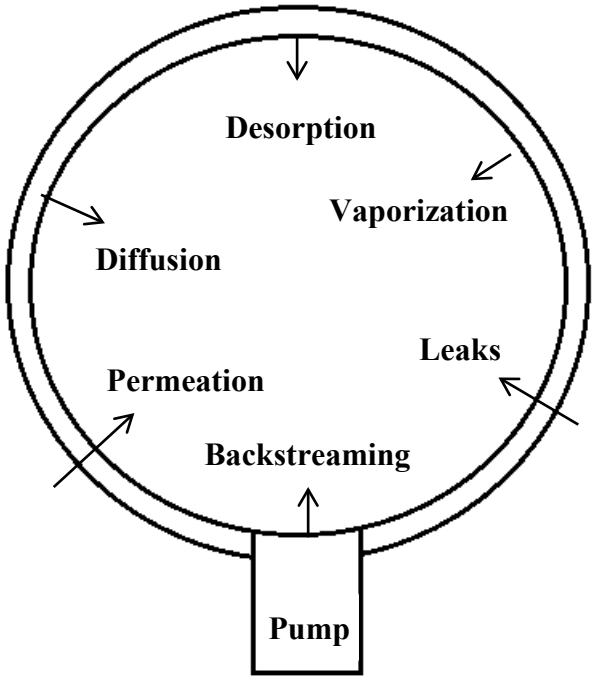
Picture 17 illustrates the working principles of these pressure measuring methods.

4.4 Creating a vacuum

A vacuum is created into a processing chamber by using vacuum pumps. The pumps' working principle is not that they attract molecules, but instead, the molecules run freely until they wind up in the pump by accident. The role of the vacuum pump is to give the molecules a preferential flow direction and prevent the trapped molecules from returning to the system. (Mattox 1998)

The vacuum pressure is quickly lowered by evacuation of the system with the use of mechanical pumps. In some cases, a ballast tank is used for this purpose. This process is called roughing. Roughing time may vary greatly depending on the system. A short roughing time can enable a short process cycle time, however, it can in some cases prevent vapors from being desorbed off surfaces. (Mattox 1998)

There are various ways that gas can get into a vacuum system, thus increasing the pressure in the chamber. Gas getting into the vacuum system can't be completely avoided, but it can be reduced with the right equipment and materials. Picture 18 illustrates the various ways that gas gets into a vacuum system. (O'Hanlon 2005)



Picture 18: Sources of gas in a vacuum system (O'Hanlon 2005)

There are various different sorts of pumps that can be used to create different levels of vacuums. Mechanical pumps are the most common. This is partly because they can be used by themselves to create a rough vacuum, or they can be used to support high vacuum pumps. Mechanical pumps can often exhaust to ambient pressure. This is something most high vacuum pumps can't do. To reach a very high vacuum, mechanical pumps are first used to lower the pressure. Once the pressure is low enough the high vacuum pumps kick in. There are many options for reaching different levels of vacuum, but in many manufacturing processes mechanical pumps offer a good enough result. (Mattox 1998, O'Hanlon 2005)

5 X-RAY MACHINES AND CHARACTERISTICS

This chapter discusses how x-rays are made and how they are used in medical imaging. Radiation safety principles and regulations are also discussed.

5.1 Working principle and challenges in x-ray imaging

X-rays are a form of electromagnetic radiation. Creation of x-ray photons happen when a substance is hit by high speed electrons. In x-ray machines, the environment needed for creating x-rays is provided by the x-ray tube. (Bushberg 2012, Hsieh 2009)

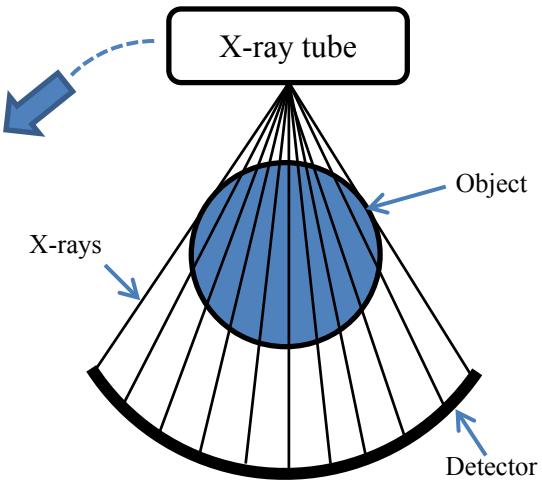
X-rays are useful in medical diagnostics because they can easily provide an image of parts of the patient that are invisible to the naked eye. Basically x-rays work in a way that when x-ray photons are passing through a patient, some are absorbed, some scattered and some pass through without any interaction. The x-rays that pass through with no interaction are detected by a receptor. The receptor can be film based or a digital sensor. The image is drawn based on the number of photons that are captured by the receptor. The areas that receive a large number of x-rays become dark in the image. Brighter area in the image has received less photons. The resulting image is a two dimensional projection of the matter the photons passed through. (Bharath 2009)

Basic principle of making x-ray image is then quite simple. However, there are several aspects that make the ideal situation more complicated. These complicating aspects are (Bharath 2009):

- Photons' statistical arrival
- Scattering of photons
- Projection lines are not parallel
- Detection of photons is inefficient
- Beam hardening phenomenon
- Ionizing radiation is harmful for live tissue

Arrival of x-ray photons is statistical. This is because the release and energy of x-ray photons varies despite having a controlled environment where x-rays are created. Consequently, the amount of photons arriving during a unit of time can only be given a probability instead of certainty. Also, detection of photons isn't perfect, which further complicates the matter. (Hsieh 2009, Bharath 2009)

When an image is created with a stationary radiation source, it is apparent that the projection lines will not be parallel. As a result, dimensions of the image do not perfectly represent reality. This is not as much of an issue when more pictures can be taken from multiple directions. When these kinds of images are taken, the x-ray tube and the detector remain stationary in relation to each other. They both revolve around a stationary object being scanned. Picture 19 illustrates the picture taking and the non-parallel projection lines. Software can then be used to calculate the real projection base on the images. (Hsieh 2009, Bharath 2009)



Picture 19: Imaging with a revolving x-ray tube and detector

Scattering occurs when radiation hits matter. It means that some of the photons change their original direction. This results in loss of energy in the primary radiation beam and can appear as a worse image. (Bharath 2009)

Beam hardening means that when photons pass through tissue, the distribution of photons passing through the whole way is different than at the side of the source. Basically, distribution shifts in the favor of photons with higher energy. This phenomenon can cause loss of image contrast, since the distribution of photons of different energy levels does not remain constant. (Bharath 2009)

It is also worth noting that ionizing radiation, which x-rays are, is harmful to living tissue. As a result, the radiation doses used in medical imaging must be kept to a minimum. This creates a challenge of balancing enough radiation to create a good readable image against not exposing the patient to any more radiation than is necessary. (Bharath 2009)

5.2 Creating x-rays

X-rays are created using x-ray tubes. The reaction starts when filament wire on the cathode end of the tube is heated with a current. Once the wire is heated enough, it begins to glow. When the wire temperature rises, electrons are emitted from the metal. These electrons are free to move away from the wire. (Hsieh 2009)

Voltage is created between anode and cathode, which creates an electric field and makes the free electrons move towards the anode. This creates a current between the anode and cathode. When voltage on the anode increased from zero, the current begins to increase. At first this happens slowly due to an electron cloud near the filament wire. This means that the free electrons can't all move freely away from the cathode. Once the voltage rises enough, the current between the anode and cathode becomes nearly independent from the anode current. At this point the electric field can pull all the emitted electrons towards the anode. (Bushberg 2012, Hsieh 2009)

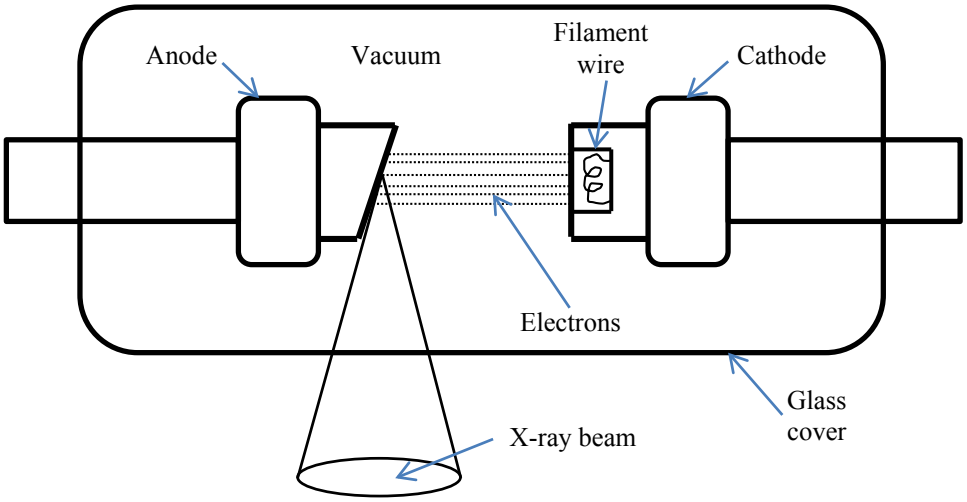
When the electrons hit the anode, most of their energy transforms into heat. Less than 1 % of the input energy actually transforms into x-ray photons. Over of the input energy 99 % becomes heat. (Hsieh 2009)

The amount of radiation that is created can be controlled with the tube current. The current directly affects the amount of electrons releasing from the cathode and hitting the anode. Change of the anode hitting electrons creating x-rays is even when the voltage stays constant. Thereby, higher current equals more radiation. (Bushberg 2012, Hsieh 2009)

Higher voltage gives the created x-ray photons higher energy. Higher energy enables the radiation to better penetrate matter. Therefore, the thicker or harder to penetrate an object is the higher voltage should be used for the creation of an image. If the voltage used is too high, the image becomes unreadable due to too much radiation going all the way through the object. (Bushberg 2012, Hsieh 2009)

5.3 X-ray tube components

X-ray tube is the radiation source of the x-ray machine. The main components of x-ray tubes are the anode and the cathode. They are in a vacuum that is held by a glass cover. Without the vacuum the x-ray tube would not work. Therefore, the x-ray tube cover must be intact for the machine to work properly. Picture 20 further illustrates the structure and the operating principle of an x-ray tube. (Bushberg 2012, Bharath 2009)



Picture 20: X-ray tube components and operating principle

The cathode is the negative electrode of the x-ray tube. Cathode has a filament wire or multiple filament wires and a focusing cup. The filament wire is usually made of tungsten. When creating x-rays, the filament wire is energized with a voltage of about 10 V and a current that can go up to 7 A depending on the situation. (Bushberg 2012)

The anode is the target electrode that creates radiation when it's hit by energy electrons. When creating x-rays, the anode is kept at a positive voltage in relation to the cathode. Most of the electrons hitting the anode create heat. As a result, creating enough x-rays to take a good image generates a lot of heat. Because of the heat, the rate of x-ray pro-

duction has to be limited. If it wasn't, the tube would wear out fast. The most commonly used anode material is tungsten. This is due to its high melting temperature and high atomic number. In some x-ray applications other materials like molybdenum and rhodium are also used as the anode material. Different materials offer different x-ray characteristics, which enables seeing some aspects more clearly in an image. (Bushberg 2012)

5.4 Radiation safety

The person or organization that uses x-rays in their operations is responsible for the radiation safety. In Finland, this means that the practitioner is obligated to follow the radiation law. Instructions for practical applications in Finland are given by Säteilyturvakeskus, also known as STUK. (Säteilyturvakeskus 2011)

In radiation work, there are tight restrictions of the allowed doses of radiation that can be caused by work. The radiation work should be designed according to the ALARA (as low as reasonably achievable) principle. Also, the highest allowed amount is 6 mSv on a zone that is defined as radiation zone. On a none defined zone the limit is 0,3 mSv. (Säteilyturvakeskus 2011)

The doze limit is set for each source individually. However, if one radiation area has multiple sources of radiation, they are to be considered as one source, when the area's radiation shields are planned and inspected. (Säteilyturvakeskus 2011)

When radiation shielding is designed, the radiating directions should be taken into consideration. There needs to enough shielding to prevent radiation from reaching the people working at the proximity of the source. Shield should be placed so that at the range of 0,3 meters surrounding or above the shielding, there should be no harmful amounts of radiation. Also, no harmful radiation 1,5 meters below. These rules have been created so that no exposure can occur during work. (Säteilyturvakeskus 2011)

In order to make sure that the amount of shielding is enough for the radiating environment, radiation measurements need to be conducted. These measurements will be done at least at the ranges that have been designed as the working distances. It may also be necessary to perform the measurements in other areas. This is because sometimes scattered radiation can get around the shielding. The fully verify the safety of the radiation work zone, measurements need to be made from multiple directions even if the shielding covers all directions. It may be that the shield is not of equal thickness all around. Special attention need to be to the material seams and joints. These have often been found to offer the weakest protection from radiation. (Säteilyturvakeskus 2011)

General requirements of a radiation zone require that the areas must have warnings to indicate the radiation danger. The warning sign for radioactive substances or ionizing radiation is shown in picture 21.

Picture 21: Warning sign of radioactive substance or ionizing radiation

No unauthorized access is to be allowed to areas that are defined as control areas. Trespassing is to be prevented by using structural obstacles, locks, or access control. At least one of the doors, leading to an area with a radiation source, has to be openable from the inside. (Säteilyturvakeskus 2011)

Building a radiation area according to STUK regulations makes sure that the people are safe and the laws are followed. In conclusion, it is important to always make sure that there is enough shielding around the radiation source. Even so, measuring the radiation around the shielding is the only way to make sure that the people around the source are not exposed to direct or scattered radiation. (Säteilyturvakeskus 2011)

6 CURRENT STATE DESCRIPTION OF PRODUCTION PROCESS

This chapter describes the state of the production process before the beginning of this research. Knowing the current state of the production process is vitally important for planning the future state.

6.1 Layout and material flow

Currently products are brought into the vacuuming area from two directions. This is due to variations between different products and limitations caused by the production area and process. Some of the products would not be productive to assemble in the same assembly cells, consequently the material flows differ between the products. The vacuuming area also has equipment that requires the operators to wear hearing protection. Partly for reasons of comfort these equipment have been placed in a separate room than work stages that do not require hearing protection.

Within the vacuuming area, the layout and the material flows are quite well thought out for the current process. Vacuum chambers have been placed in four rows. Material comes from one of the two neighboring rooms where the THAs are made ready for the vacuum process. Current layout and material flow are presented in attachment 1.

There are several limitations for optimizing the material flow. First reason is that in order to achieve a good vacuum as fast as possible, the vacuum pumps need to be close to the chambers. Since the pumps are very loud, they need to be placed in a separate room so that the operators don't have to wear hearing protection during the entire THA production. Second reason is that since the vacuum process cycle time is so long, compared to the takt time, there is a need for many chambers for the products. Consequently the chambers take a lot of space which limits options for their locations. There also needs to be enough space for the oil chambers and the oil barrel from which the chambers are filled.

6.2 Description of vacuum process

This chapter describes the process of filling THAs with oil. As it has been stated before, it is extremely important to avoid getting any impurities inside the THA. This includes even the slightest amount of air. Impurities can cause disruptive discharges, which would cause the THA to fail. The process chart is presented in attachment 2.

Once the vacuum process is finished, the THA is taken into the leakage test and other finalizing processes. While the vacuum process has a lot of steps, the operator time is relatively short. This will be examined closer in the next chapter.

6.3 Average lead time of vacuuming process

Most of the vacuum process cycle time comes from two process steps. The most time consuming stage is vacuuming before oil is poured into THAs. Second most time consuming stage is vacuuming after THAs have been filled with oil. These two steps combined already put the vacuum process cycle time at a very high level, without taking other steps into account.

Flow chart of the vacuum process is presented in attachment 3. The total lead time and every process step are presented in the attachment 4. About 99 % of this time comes from the two steps that include vacuuming and require no effort from the operator. This goes to show that if the vacuum process is to be shortened, in any significant way, it must be done mostly by shortening the vacuuming steps of the process.

The values have been acquired by timing the process with different operators and counting the averages. It must be noted that some of the steps may not apply for all products. However, the most time consuming steps are done for each THA.

6.4 Production control and material requirements planning

The entire factory's production is controlled by the customer demand and in some cases estimated demand of near future. Most of the products built in the factory have an order before the assembly is started. Aim is to keep buffers to the minimum and thereby reduce the amount of capital tied to storage. Keeping the buffers to minimum is also used as a way to make problems visible as fast as possible.

While the inventory is kept to minimum, there must always be enough parts to keep the production running. To keep up the balance of low but sustainable storage levels, all parts have been classed based on their criticality, estimated demand and delivery time.

Kanban is widely utilized around the factory. This is to make sure that parts are ordered in time and in predetermined batches. Kanban also ensures that less capital is tied to the inventory and the storage rotation is better than it would be without Kanban. The amount and the size of kanbans are checked when there are major deviations in the predicted demands certain products.

THAs are manufactured based on the playbooks of the production lines that make the final assemblies. To ensure that sudden changes don't cause delivery problems, some THAs are kept as buffer. The size of the buffer is dependent on the usual consumption of the specific product and the lead time of the entire THA production process.

6.5 Product deviations

The products constructed in the Tuusula factory can be divided into two main groups: intraoral and extraoral X-ray machines. Both product groups, and every product included within them, go through the vacuuming process with almost exactly the same cycle time. Slight deviations exist, but as vacuuming is the longest process step, there are no major differences between products.

Structural differences between the products do have a slight effect on the time it takes to reach the desired pressure. However, the differences are so minor that altering process control between products would not be beneficial. This is the case with the current process.

When the vacuuming time is reduced, the structural differences may play a major role in how long the THA requires vacuuming. Since, it has been noticed that air takes a different time escaping from different products, products require independent testing.

In addition to different physical structures, the different products are also exposed to different stresses during their operation. Differences exist in the operational voltages, currents, exposure times and cooldown times. The products may also be used in different angles. This however does not have much of an effect since all the THAs are fully filled with oil and the THAs' internal parts can't move.

These differences mean that even if we could assume that air escapes all THAs in the same time, the same time in the vacuuming time might still not work for all products. This is because with different voltages and currents, same amount of air could not be any issue for one product, while being potentially catastrophic for another.

Unfortunately there are no reliable ways to estimate how long it takes air to escape different kinds of structures. As it was presented in the theory of vacuuming technology, there are a lot of ways a vacuum system can be contaminated. There is also a large random factor to air escaping a system. The factor is increasingly random with complex structures. This is why it would simply be too hard to attempt simulating how the air escapes the products. This is also why results of for one product don't and can't be assumed to apply for other products.

7 CURRENT STATE ANALYSIS OF PRODUCTION PROCESS

To create beneficial and executable development plan, there must be clear understanding of the strengths and weaknesses of the current process. This chapter provides an analysis of the current process. The problem analysis is considered confidential, so it can be found in the attachments.

7.1 Analysis of layout and material flows

Currently the vacuuming process is in a separate room from the assembly and testing stages of the THA production process. This solution is not optimal for creating flow to the process. The products are not as close to the next process step as they would be in an optimal layout.

Picture of the current layout and material flow is presented in attachment 1. Some of the limitations that the process has are due to both walls and loud machines. To create better flow, some walls would have to be brought down.

7.2 Average lead time and deviations of vacuum process

Vacuuming process begins with the tube heads being prepared for the vacuuming. Preparations include placing a funnel on the tube head and in some products covering areas where oil is not allowed to flow. Once a line of chambers have been filled and the covers put on, the suction valves are opened and the vacuuming begins. This process is repeated for each of the three vacuum lines. When all three lines have been filled and suction has been switched on, it takes a long time for the pre-vacuuming to be completed.

The pre-vacuum alone would create a bottleneck in the THA manufacturing process. When it is combined with the vacuum that follows oil filling, they make the rest of the process steps insignificant in duration.

All deviations that exist in the vacuum process are separated from the actual vacuuming. Since the vacuuming takes such a long time, these deviations are unimportant when the lead time is considered.

7.3 Required capacity estimation

There are major deviations in the order base during the year. Existence of these deviations is well known and they can be estimated to a point. There have rarely been any issues with the vacuuming capacity. When such cases have occurred, they have been due to some deviation in the previous stages of the production process. This can happen when for example a machine from a previous process stage has been under maintenance the previous day. This could cause too many products to flow into the vacuum process during the following day.

While the demand of products can be estimated, changes on the global market make the predictions somewhat unreliable. Market growth can be quite well predicted. The im-

pact of marketing campaigns and new products can have an unexpected result. Also, changes in strategy may change where some products are manufactured.

Because of the existing uncertainties, estimating the exact capacity needed is not simple. This is why there is usually more vacuuming capacity than is actually needed. Another reason for the extra capacity is the long process time. Since the process isn't flexible there has to be enough capacity to put through more than the usual amount of products if needed. The current duration of the vacuum process leads to a situation where deliveries can be late, if products can't fit into any of the vacuum chambers when they arrive at the process.

Predictions of the future demands will not be handled in this thesis as they are considered confidential. Therefor the exact future capacity will not be disclosed. The capacity for vacuum chambers is counted with the following equation.

$$\frac{daily\ maximum\ demand}{daily\ output\ of\ one\ chamber} = number\ of\ vacuum\ chambers$$

It must be noted though, that there are products of different sizes. Some products fit into the chambers in higher quantities than others. Also, this equation applies with the current process. If we modify the equation to take into account the different products and the future process, we get the following equation.

$$\frac{demand_1}{output_1} + \frac{demand_2}{output_2} + \cdots + \frac{demand_n}{output_n} = number\ of\ vacuum\ chambers$$

Of course, any number that comes out from this equation needs to be rounded up to match the maximum demand. Also, when estimating the demand it must be kept in mind that sudden changes can occur. If one assumes that the amount of equipment needed can be calculated based on demand of the past, the capacity might run out when orders start coming in. This is why the number received from the presented equation should only be considered directional.

8 VACUUMING TESTS

This chapter discusses the testing that is performed to define the necessary vacuum process duration. Tests will define the parameters for the future stage of the process. Many different products need to be tested to make sure that the results are reliable and the process can be changed for all products. The testing process will be carried out in a way that doesn't interfere with the production customer orders.

The first assumption is that prolonging the vacuuming process from its original length would not accomplish any quality benefits. This assumption will not require further proving, if the tests show that the current process can be shortened as planned. Furthermore, the assumption is supported by few customer returns that could be considered to be the result of insufficient vacuuming. In fact, no returns can reliably be said to be related to the vacuuming process.

As fully assembled THAs are very expensive, tests will also include testing of subassemblies to reduce to need to test completed THAs. These tests will be designed to strain the most fragile parts of the products.

It was also considered to simulate how the air escapes the THAs. However, as discussed in chapter 4, such simulation is virtually impossible for complex structures such as x-ray THAs. This is because there are a lot of random elements involved when air escapes such a structure. The process would include molecules getting emitted from the structure and then either get bounced off or reabsorbed from another part with little predictability. Even if a somewhat working simulation model could be made, it would only work for a certain product. These are the reasons why no gas flow simulation will be attempted and all tests will be conducted empirically.

The two main variables to be tested are the vacuuming time before the oil is poured in and the vacuuming time once the products have been filled with oil. These variables can change the amount of air and moisture that remains in the THAs after the process is completed. The assumption is that both times can be significantly shortened without meaningful, if any, changes to the residual moisture or air.

The vacuum pressure will also be under observation. It will be ensured that the pressure reaches the right values for the vacuum process. These values have been predefined in the process instructions.

The actual test plan will not be presented in this thesis. Neither will the results of the tests be presented. This is due to the highly confidential nature of the vacuum process. Rest of the testing chapter will therefore remain in the unpublished attachments.

8.1 Safety during testing

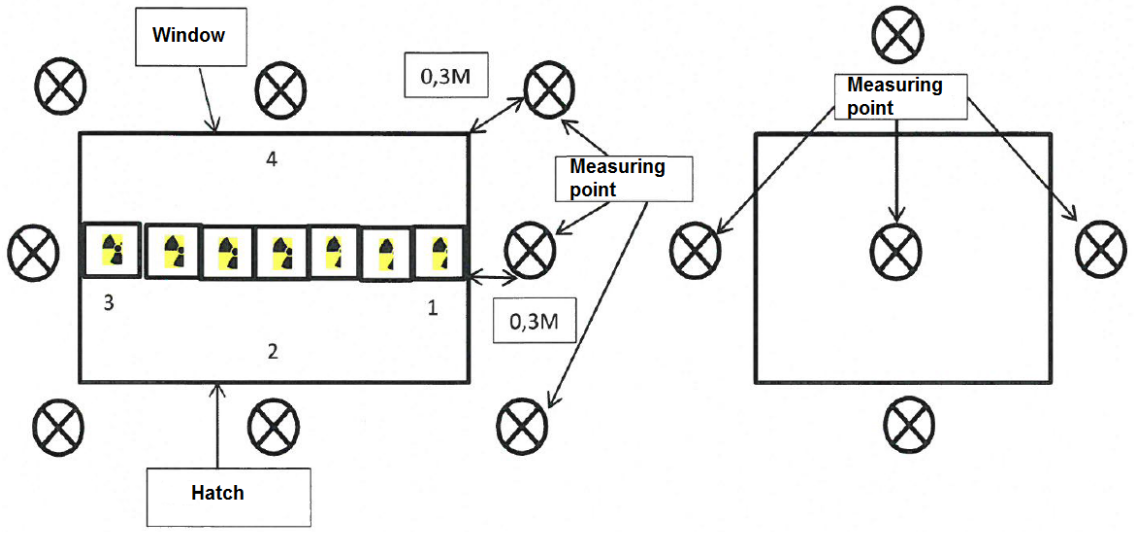
Testing processes included working with radiation sources and high voltage circuitry. Therefore, making sure that the tests were conducted safely was very important. The most important component of the safety aspect was that people working with the tests had the right knowhow.

All testing personnel had been in radiation safety training before being involved in the tests in any way. People designing and making the test equipment were all from the electric department and approved for such work.

In the testing area, the on/off switches were located at a safe distance from the radiation sources. This was to make sure that no-one would have to go within the radiation zone to turn off the devices.

Radiation safety during the tests was the first concern. The THAs were set to radiate away from the operators. Lead shielding was added to ensure that scattered radiation does not hit the people working in the proximity. Radiation measurements were made to ensure that the values would not be too high.

All tests were carried out according to the ALARA principle. In this sort of testing it basically meant that the radiation levels were not allowed to be higher than the background radiation. Picture 22 presents the way one led-shielded testing cabinet was measured for radiation.



Picture 22: Radiation safety measurement

The testing presented above proved that there was no direct or scattered radiation in the testing area. Tests were conducted by making measurements from all sides of the cabinet that had several radiation sources inside.

The first and most important goal in the safety design was to ensure that no-one would be exposed to radiation because of the tests. Secondly it was made sure that if this would happen, despite all precautions, it would not go unnoticed. This is why all personnel working with the tests had personal dosimeters that measure how much radiation a person has been exposed to. Dosimeters have not measured higher than allowed amounts of radiation. This means that test operators have not been exposed to too much radiation.

8.2 Test plans and results

All test plans and results are considered confidential and will not be published. These will be included in the attachments.

9 PRODUCTION DEVELOPMENT PLAN

Content of this chapter is confidential and will be included in the attachments. The attachments won't be published.

10 RESEARCH RELIABILITY EVALUATION

The research was done using statistical testing methods. The confidence level, that will be reached when all tests are done, is very high. This suggests that there is very small chance that the products manufactured with the new shortened process would be any worse than those made before. The confidence is purely based on the endurance tests.

Reliability of the result is further increased by the other tests that have been run. All the other tests supported the conclusion that the shortened vacuum process will not cause any quality issues.

The research applies reliably to the products that have been tested. There is a good chance that the results apply for other products as well. However, since all the products have not yet been tested, the chance to reduce the vacuum process time for the untested products remains speculative.

11 CONCLUSIONS AND RECOMMENDATIONS

At the time of finishing this thesis, tests are still running to finally conclude whether the shortened vacuum process is equal to the longer one. So far there has been no indication that the THAs' quality will be any worse than those that have been manufactured with the current process.

First recommendation is that the tests be finished as planned. If after finishing, the results remain unchanged, it is recommended that the process is shortened to the tested level for all the tested products.

The products that remain untested should be tested if there are still plans to manufacture them in large numbers. If there are no such plans, these products should be manufactured according to the current process due to the long testing time and relatively high cost of further testing. With two overlapping processes, there is also a risk that wrong process will be applied to a product. This should be taken into account when the final decision is made.

New funnel tools should be created to compensate the difference in vacuum pressure of the oil and the products to be filled. This should be done when the tests are close to finishing. Not doing this would lead to time being wasted on cleaning the vacuum chamber walls. Also, oil would be wasted in small amounts.

Overvoltage tests brought up a question of whether the vacuuming process is even necessary at all. While these tests did not fully meet the normal operating conditions, they showed that the vacuuming process is not as important as previously thought and the components are more durable than expected.

When the new process is proven to be reliable enough for implementation, kaizen event will be kept to improve the visual control of the vacuum process. The future process will include several products that may be in a different stage of vacuuming. Therefore, the operator will need to know how long certain products have been in the vacuum.

Currently the vacuum pressure is checked once per cycle. This is enough as all products have come from a vacuum, pressure of which has been checked. In the future, the process will require more control. Otherwise a pump failure might go unnoticed, leading to "badly" vacuumed products moving further in the production process. With the current system the increased control would create a lot of extra work and could be easily forgotten. This is why it is recommended to make the pressure control automatic. Automatic alarms should indicate if the pressure does not drop at the minimum rate required.

Daily management should be used to minimize the risk of operator failures during the process transformation period. This means going through the changes with all the operators and training them in the new process. In the beginning, the control should be daily. Once the new process has been running for a while, less control is required. In support of the training, the work instructions are to be meticulously rewritten. This is to ensure that all process related questions can be answer by getting acquainted with the instructions.

The instructions should be updated before the testing is finished, so that it will not cause any delays to the implementation of the future process. This also applies to all the other tools that will be taken into use to aid in the process.

If the product volumes increase, investing in more vacuum pumps should be considered. With the shorter process, the current chamber capacity would be enough to meet a far greater demand. However, with much greater volumes, there would not be enough pumps to reach the desired vacuums fast enough.

Finally, it is recommended that the operators are encouraged to give open feedback of the new process. The operators should especially be listened to during the early implementation stage. This is to ensure that the operators don't forget the issues and simply work through them. Additionally, the operators are the ones most likely to spot any potential problems. Asking for feedback should be part of daily management.

The basic way of how the process is done will remain the same. There is therefore no risk that the operators would have any problems learning the new process. This is assuming that they know exactly what has changed and how it affects their work.

12 SUMMARY

This research was set up to find out if the lead time of vacuum process of X-ray tube head production at Kavo Kerr Group Tuusula can be shortened by at least 50 %. This goal was to be accomplished without a negative quality impact. Additional goals were to map out other possibilities for improvement in the vacuum process.

Testing of the shortened vacuum process has been conducted mainly by endurance testing of the THAs. Other forms of tests were also carried out in attempt to bring out quality differences between different vacuum times.

As the testing has not yet been completely finished, there is no certainty that the vacuum process will be shortened as planned. However, based on the tests done so far, it seems very unlikely that the shortened process would reduce the quality of finished products. Additionally, all the tests conducted to date, have been done with a far shorter vacuum time than the original goal.

Both the endurance tests and other supporting tests have suggested that the vacuum process is not as critical as previously thought. The tests have shown that some products could possibly skip the entire process without compromising quality. This has not been thoroughly tested, so further testing is required if the process is to be dropped out for any product.

Test equipment is ready for all the high volume products and the tests to continue running. The final decision, of if and how some of the lower volume products will be tested, has not yet been made. If the decision is made that all the products will be tested with the shortened vacuum process, the same test plan can be applied for that purpose. Decision of expanding the tests will be based on a payback analysis. The products will have to be manufactured for spare parts at least for the next 10 years. If two different processes remain, it will also cause a potential risk of the shortened process being used for products that have not been tested with it.

Several improvement opportunities were found within the vacuum process. If implemented, these will reduce risks of operator error, improve ergonomics and create a possibility of further shortening the process.

All results indicate that the process can be shortened by more than 50 %. This suggests that the research has been successful. However, the testing continues for a few more months. If the results remain unchanged, a very high confidence will be reached that the reduction of vacuum time will not cause any increase in quality issues.

Tests seem to be successful in proving that the process can be shortened as much and even more than originally intended. The tests have in fact not found the limit when a shorter process would cause quality issues. This means that once the tests have been finished, and the new process implemented, there is a good chance that the process could be shortened even more. This may be a cause for further testing in the future.

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